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THE EARTH, THE SUN, & THE MOON

By GEORGE FORBES

M A (Cantab), Hon LL D (St Andrews), F R S

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THE EARTH, THE SUN, AND THE MOON

CHAPTER I

THE EARTH

In ancient days the most natural supposition about the stars was that they were points of light stuck upon the spherical vault of heaven, and that the planets and other " wanderers " were similar points of light that were crawling, or being moved, over the surface of this vault, among the fixed stars. This spherical shell was supposed to rotate round the fixed flat earth once in twenty-four hours, carrying with itself stars, planets, sun, and moon. In those days it was natural to suppose that our fixed world was a flat surface or disc.

After it had been discovered that the members of the solar system, at least, were all at different distances from us, the heavenly vault theory ceased to hold. Then it was found to be *simpler*—and therefore (as Sir Isaac Newton always insisted) more likely to be true—if we suppose the earth to be a round ball rotating upon an imaginary axis passing from the North to the South Pole.

The principal use that an astronomer has for the earth is as a solid steady foundation upon which to fix his observatory with its telescopes and other devices for observing the orbs of heaven, and for fixing their position among the other stars. This last is the greatest fundamental necessity for reaching truth through a study of the heavens, and no obstacles can be allowed to detract from the accuracy with which star-positions are determined. It is for this reason that he seeks to place his instruments on the most solid, enduring foundations that he can find. Under these circumstances it is a veritable calamity that he can find no more secure foundations than this most unsatisfactory and utterly unsuitable locality, the earth which we inhabit. Except under compulsion, he would have refused to make use of it for his purpose.

The surveyor of any country who desires to fix the positions of buildings and mountain-tops, for making a map, takes care that the theodolite, or the level, with which he measures the angular position of terrestrial objects, is fixed solidly on an immovable base. The astronomer who wishes to fix the position of stars would like to do the same, but such a place is not to be found, and he is forced, *nolens volens,* to build upon this unsuitable earth which he knows to be unstable, in constant motion, with fluctuations both in the direction and the amount of its motions. The surveyor would be in a bad way if he had to fix his theodolite on one of the swing-seats of a whirling "merry-go-round." Yet this is what the astronomer has to do. The earth upon which he has to fix his telescopes, transit-circle, and altazimuth, is whirling round all the time, once in twenty-four hours. Even the situation of the astronomer's whirling platform is not fixed, but wanders round the sun, with a variable speed, to places nearly 200,000,000 miles apart in the course of six months, while he is pointing his instruments to the stars to compare their positions.

The sailor, in a somewhat similar position, eventually overcame to some extent this same difficulty of observing accurately the positions of sun, moon, and stars from his rocking platform by the invention of the sextant. The astronomer has met his own difficulties arising from a similar cause by a like industry in devising instruments and methods for frustrating the obstacles of unsteady foundations. He makes the best of it. He studies the motions of his moving platform, and discovers mathematically all the corrections that must be made to his observations, in order that they shall be freed from the many sources of error imposed by the earth's movements.

The rotation of the earth on its polar axis, and its revolution round the sun, are not the only irregularities of which he has to complain.

The pole of the earth is not perpendicular to its orbit round the sun. The polar axis of the earth points to a position among the stars some 23 degrees away from the pole of the earth's path round the sun. Hipparchus, the great Greek astronomer, some 150 years before the Christian Era, discovered that the earth's pole travels round the pole of its orbit among the stars. It completes the circuit once in 26,000 years. It now points to a star in the Little Bear. Twelve thousand years hence the earth's axis will point nearly to Vega, in the Lyre, in a totally different part of the sky.

This movement of the earth's polar axis in a circle was proved by Sir Isaac Newton to be caused by the attraction of gravitation, towards the moon and sun, of the equatorial bulge in the earth's figure; for the earth is not a true sphere. But the moon's action varies during a lunar month, being greatest when her position among the stars is farthest from the celestial equator, and being zero, twice in each month, when on the equator. This fact, and others due to the irregularities in the moon's motion, cause the amount of the movement of the earth's pole to be constantly changing.

Thus, while the astronomer uses the direction of the North or South Pole as one of his data of position (his only other datum being the direction of a plumb-line), he has to make corrections for the ever-changing direction of the pole. Still further, recent researches show that the axis of rotation of our earth is not even fixed in the earth itself. The North or South Pole is a point on the earth's surface, constantly changing its place over a little space comparable in size to a cricket pitch.

These are a few of the difficulties introduced into the astronomer's life by the instability of the earth as a foundation on which to place his instruments.

The difficulty of making accurate observations of star-positions is enormously increased by the atmosphere surrounding our globe. A ray of light is bent out of its course when it strikes the surface of our atmosphere obliquely; just as the part of an oar that is under water seems to be bent where it meets the water. So it happens that, when we see a star in the middle of a telescope's field of view, the telescope is not really pointed to the star, but to a higher point in the sky. The ray, in passing through the atmosphere, takes a *curved* path downwards, owing to increasing density of the air near to the earth's surface. This error in the observed position, called the "*refraction error,*" has to be measured from the results of long-continued observations. It is almost insensible in the zenith, and greatest at the horizon. In fact, at the moment when we see the sun's disc complete, with its lower limb resting on the sea-horizon, at that moment the sun has really set. It would not be then visible at all but for the large horizontal refraction which raises the apparent position of every object in the heavens.

The astronomer's difficulties in fixing star-positions were increased when he discovered a further reason why he does not see a star in the direction where it really is.

In a steady downpour of rain without wind you hold your umbrella upright if standing. If walking fast you point it forwards to shield your body. In the same way, when looking at a star through your telescope, the rays of light would pass straight through if the world and the observer were at rest. If they are moving in any direction, the telescope must be pointed forwards in that direction, as with the umbrella. This error in the observed position of a star, due to the earth's motion compared with the velocity of light, *was discovered by Bradley, the Astronomer Royal, who died in 1762.*

After we have taken note of all the difficulties in the way of using our earth for accurate astronomical observations, it seems at first to be a sheer marvel that these enormous difficulties should have been faced so bravely, and with so great success, as to lead even to the limited amount of knowledge about the stars that we possess in this twentieth century of the Christian Era.

WHAT IS A PROOF?—Different people have different opinions as to what constitutes a real proof. This is true even in science, as is easily seen by a comparison, for example, of the textbooks on geometry and on biology. The rapidly growing habit among those who read about science of relying entirely upon *authority* for their scientific convictions and beliefs is not always wholesome, and would be checked if those readers would try to detect and examine any flaw they may suspect in an argument which may be sometimes put forward with too little detail, and accepted too often on the authority of some high priest of science.

To illustrate what is meant by a proof, let us take some absolutely certain, well-established astronomical fact, about the answer to which there can be no doubt whatever; and let us learn to appreciate the wisdom of the man who declines to rely upon authority as the basis of his scientific beliefs.

IS THE EARTH ROUND OR FLAT?—*We all know that the earth is an oblate spheroid, revolving round the sun in 365¼ days, and rotating once in every twenty-*

four hours of sidereal time. Here we pause and ask: "Do we know it?" The great majority would say: "We do know it, because we learned it from the highest authority. This is not knowledge. How many would be able to say, from their own personal observation and experience, whether the earth is round or flat? Galileo thought he was proving the earth to be round when he observed its shadow on the moon, during a lunar eclipse, to be circular. The flat-theory man might have asked: "What shape would the shadow have if the earth were a round flat disc?" The argument that people had sailed round the world and had come back to the same place would have been answered by the suggestion that really those people had been sailing on a circle round the flat earth. When they came near to the edge of the disc they met impenetrable snow and ice.

No argument can be really convincing if it is not entirely understood from beginning to end. Otherwise it can only be "accepted on authority." The most usual *proof* of the earth being round is no proof at all, as was found out by a delightful man, who spent all his time in breaking stones at the roadside, in thinking, and in talking, while he worked, to one of the many friends who enjoyed his conversation. Here is *a tale told by the stone-breaker:* "I have friends, even learned college men, who talk to me, while I work, about things they can teach me. And afterwards I break many stones in going over their arguments. If I follow what a college chap says, and take it as proved because he is a learned man, it may all seem reasonable; but, deep down inside me, I am sometimes very sure that my college teacher may be wrong. After I have broken a heap of stones the weak point of his argument suddenly strikes me.

"To give you one example, I must tell you how Mr. A., a clever young fellow, fresh from the University, tried to prove to me that the earth is not flat. I know well enough that it is round, but I hold that he did not prove it. And, moreover, I can see no hope of ever really proving to myself what I know to be true—that the earth is not flat. Mr. A. told me all about the way we see a ship going away from here beyond that horizon; how the horizon first cuts off the hull, then the sails, then the top of the masts; and then the ship disappears. He said this proved that the earth is round. I had a feeling he had not told me all that was needed to prove this. I hummed and hawed a little. So he took out of his pocket a book by a great astronomer, and read to me these words, which I copied out at home: 'The observation of a ship at sea is sufficient to prove the curvature of the ocean surface. The ship seen from the shore, or the shore seen from the ship, shows the lower parts of the ship or shore cut off by the sea horizon as the ship goes farther out to sea. This double fact demonstrates in an evident manner the convexity of the sea. If it were a flat surface, distance alone would cause the losing sight of the ship with its rigging; and the low parts of its hull would not be hidden before the top-masts.'

"I had a feeling inside me that this last sentence need not be true. There might be ways of explaining what we see, even if the earth is flat. I broke many stones on this pile here before I could put it into words. At last it was clear to me. I do not know in what way light comes to my eye from a star, or a lighthouse, or the hull of a ship. But it seems quite probable that in passing through our atmosphere it may rise in the air, as smoke does. So a ray of light that starts from the hull of the ship in a straight line for my eye would pass above me altogether. If the earth is flat, the ray that hits my eye must go in a curve, a little downwards at first. Then, rising as it travels through the air, it may hit my eye. If that ray from the ship's hull just grazes the flat ocean, it would seem to me to be in the same line as the horizon. If the ship is farther away, no ray from the hull can possibly reach my eye, while rays of light from the mast still do so. Thus, I say, if the earth is flat, the hull of the ship may still be the first part to disappear. Mr. A. and the great astronomer had assumed that light travels in straight lines; I suppose they must have tested this and found it to be true, but I cannot see how I can ever prove this for myself.

"Mr. A. gave me another of his proofs. Three poles were stuck each to a height of 6 feet above the water in a straight canal, in a line, at half-mile distances. Looking over the top of No. 1 at the top of No. 3, it was found that the top of No. 2 was higher up, because, as he said, it was raised up by the curvature of the canal's surface. That would be true if light goes in a straight line. But if a ray of light rises in the air as it goes along, the ray from pole No. 3, in passing to my eye at pole No. 1, must pass below the top of pole No. 2.

"I would like to know how they prove that light always goes in a straight line. It would make me very happy to see them doing it. It seems to me that Mr. A. and the astronomer did not prove that the earth is not flat. All that they did was to show that *the manner in which a ship disappears beyond the horizon is not inconsistent with the opinion that the earth is round.*"

The final moral of this tale told by the stone-breaker might be advantageously absorbed by some of our modern and more speculative astronomers. His argument was perfectly sound.

THE SEASONS.—Once in every twenty-four hours the whole vault of heaven, carrying with it sun, moon, and all the stars, seems to be rotating round a line which points from our position on the earth to the pole-star (or, more accurately, to a fixed place among the stars, close to the pole-star). In reality it is the earth itself that is rotating once in twenty-four hours in the opposite direction to that in which the sun, moon, and stars seem to rotate. It rotates round its own polar axis, which is a straight line that would pass through the earth's centre and point to the pole-star, emerging from the earth's surface at the North and South Poles.

We notice that the sun behaves differently, in its daily journey from east to west, at the different seasons of the year. At certain dates in spring and autumn, [illegible] over the world, the sun rises and sets due east and west, at 6 a.m. and at 6 p.m. exactly. And then, as at all seasons, it attains its greatest height in the sky at midday, in the south to us in England, in the north to Australians or people at the Cape of Good Hope. This maximum height in the sky at midday is much less in winter than in summer. In the latitude of England we find the sun's midday height above the horizon to be in summer about four times as great as it is in winter. This causes the heat at one season and cold at the other.

This fact is familiar to all of us, and its meaning can be made much more clear by imagining a model of the sun and earth, two balls on a flat, horizontal table, at any distance apart, say one foot or one yard. The model earth goes round the model sun once in 365¼ days. It also rotates on an axis once in twenty-four hours. This axis through the North and South Poles does not point straight upwards. It points to the pole-star, which, with respect to our model, would be a good bit away from the vertical and on the north side of the table. During every part of the earth's revolution round the sun—*i.e.*, at every season of the year—its axis is pointing in the same direction—that is, away from the vertical and towards the pole-star in the north.

Now see what happens. When the model earth, in its annual journey round the sun, is at the north side of the model sun, the southern half of the earth gets full sunshine, and the northern half gets less sunshine. In fact, the North Pole and the Arctic regions have no daylight. Darkness reigns during every hour of the twenty-four at midwinter. When, on the other hand, the model earth, in its annual journey round the sun, is to the south of the model sun, the Northern Hemisphere gets full sunshine, and at the North Pole and Arctic regions there is no night, while at the South Pole and Antarctic regions night reigns during the whole twenty-four hours. In spring and autumn, when the days and nights are of equal length, both hemispheres get the same amount of sunshine.

DIAMETER OF THE EARTH.—It is impossible to measure the distance from the earth's surface to its centre with a two-foot rule or a tape-measure. If, however, we find a plan for measuring the earth's circumference, we shall then also know its diameter, assuming the earth to be a sphere.

For mathematicians have proved that the circumference of any circle is about 3·14 times its diameter.

A more exact figure is 3·141592653589. And it is rather surprising to find that this long row of figures can be easily remembered by counting the letters in the following (Archimedes being spelt with *x* for *ch*):

> " How I wish I could recollect of circle round
> The exact relation Arximedes found."

To measure the circumference of the earth, we need not carry a tape-measure all round the world, through 360 degrees. If we measure accurately on its surface in a north and south line over 1 degree of latitude, and multiply by 360, we get the earth's circumference. A surveyor can measure very long distances by a process that is called "*triangulation.*" He first measures an accurate straight base-line some miles long by means of carefully measured metal bars. At the ends of the base he points his theodolite on some distant mark, to get its direction compared with that of the base-line. Then he can deduce the distance of his mark, and so he gets longer base-lines of known length. He extends this by a series of triangles stretching northwards until he has reached a place whose latitude is 1 degree from his base. (The latitudes are got from star-observations.)

He has then no difficulty in finding that the length of 1 degree, at his part of the world, is, say, 69 miles exactly. Multiplying by 360, the circumference of the earth would be 24,840 miles, if the curvature of the earth is everywhere uniform. Many such arcs of meridian have been measured, some covering 30 degrees of latitude.

It is known, however, that the earth is not round like a ball, but is flattened at the poles like an orange. Hence the length of 1 degree, or an arc of meridian (north and south) varies with the latitude. At the Equator it is 68·7 miles, and 69·4 miles at the Poles.

The Equatorial radius of the earth is 3,963·34 miles.

The Polar radius of the earth is 3,949·99 miles.

This bulge of material on the equator is due to the centrifugal motion of the earth's rotation. Newton foresaw it, and made use of it to explain the rotation of the earth's Polar axis round the pole of its orbit in 26,000 years. The sun does not attract the ring exactly as it would if the material of the ring were all at the centre of the earth. The sun, and the moon too, exerts a twisting force upon the Equatorial bulge or ring; and this gives a twist to the whole planet and to its Polar axis. In this manner Newton explained by gravitation the wonderful discovery of Hipparchus about 150 B.C.—the great but slow movement of the earth's poles.

Newton saw that the Equator must be further than the Poles from the earth's centre. It follows that the force of gravity diminishes slightly as we pass from high to low latitudes. This can easily be detected by a pendulum clock, which goes more slowly when diminished gravity at the Equator reduces the weight of the pendulum bob.

This prediction of Newton's—that the rate of swing of a pendulum would prove that the earth's diameter at the Equator is greater than in higher latitudes—was of great importance to astronomy and to geography. For this reason, Edmund Halley was sent from this country with a pendulum to measure its rate of swing at many places, from Great Britain to the Cape of Good Hope. He entirely confirmed the prediction of Sir Isaac Newton.

The Earth's Rotation.—The most beautiful proof that the earth is rotating is the splendid experiment made by Foucault in 1851. He took an iron ball about a foot in diameter to the Pantheon, where he was able to hang it by a wire some 200 feet long. A circular rail about 12 feet across was placed round the hanging ball, and was covered with a layer of sand. A pin was at the bottom of the ball, to mark on the sand its direction of swinging. To put the ball in motion it was pulled out beyond the rail, and held in place by a thread of cotton till completely at rest. Then the cotton was burnt, and the ball started, without any jar, to swing to and fro. The pendulum was free of the earth's rotation and continued to swing as it started. But the floor of the Pantheon was rotating with the earth. So at each swing the pendulum-pin cut the sand-layer at a new place.

This most instructive experiment is delightful to watch, and, with care, can be easily repeated.

Mean Density and Mass of the Earth.—By some inexplicable insight on the part of Newton, he was able to estimate the density of the earth as between five and six times that of water—far greater than the average density of material on the surface of the globe.

Maskelyne (Astronomer Royal in 1774) found that the massive mountain, Schiehallion, in Perthshire, attracted a pendulum out of the vertical. He measured the amount, and thus compared the weight of Schiehallion with that of the earth.

Still more exact methods have now been used, and we now know that the mean density of the earth is five and a half (exactly 5·515) times that of water. What a wonderful estimate was that made by Newton, as stated above, of the density and mass of the earth! The mass of the earth is six million million million million kilograms.

Astronomical Distances.—So soon as the shape and size of the earth are known, it is easy to find out by geometry the true distance between any two observatories, and the direction of a straight line that would join them through the interior of the earth.

So a line connecting Greenwich Observatory with the observatory at the Cape of Good Hope can be used as a surveyor's base to get the distance of the moon, whose mean value is 238,857 miles, say 240,000 nearly.

But to apply this method to find the much greater distance of sun or planets at all accurately baffled astronomers until Sir David Gill accomplished it. He measured the distance of Mars when nearest to us in 1877, from the Island of Ascension, by using a heliometer for fixing the exact positions of Mars. This instrument in his hands was marvellously accurate.

It is not easy, however, to fix the exact position of the centre of Mars' surface. Gill knew that one of the thousands of minor planets which look like points of light, and whose orbits lie between those of Mars and Jupiter, would lead to more accurate results. In this way he found the sun's mean distance to be 92,880,000 miles. He then proceeded to attack the stellar distances by the same surveying method, using the diameter of the earth's orbit as a base. This was the beginning of systematic work on the distances of stars.

This problem of measuring the distances of different stars is, perhaps, the most important desideratum in the whole of astronomy. The subject is of great interest, but does not lie within the scope of the present book.

SUMMARY OF CHAPTER I

The astronomer uses the earth as a foundation on which to place his instruments. The earth is a round ball rotating once a day on an axis which always points to the pole of the heavens, and the earth revolves round the sun once a year. When we know that light travels in straight lines, a ship's gradual disappearance over the horizon proves the earth to be *round*. Foucault's pendulum experiment proves the *rotation* of the earth.

The axis of rotation is inclined at a considerable angle to the flat surface on which the earth moves round the sun. This inclination causes winter to be cold and summer hot. It also brings winter to one hemisphere when summer reigns in the other.

The diameter of the earth (about 8,000 miles) has been measured by surveying distances on a north and south line, over a definite portion of the earth's circumference as determined by astronomical observations of latitude.

Using a definite portion of this diameter as a surveyor's base-line, astronomers have used their methods to measure the diameter of the earth's orbit (about 186,000,000 miles).

Using a definite portion of this enormous diameter as a base-line, astronomers have measured the distances of stars. (The nearest one is twenty-six million million of miles from us.)

CHAPTER II

THE SUN

"*That punctual servant of all work, the sun, had just risen and begun to strike a light on the morning of the thirteenth of May, one thousand eight hundred and twenty-seven, when Mr. Samuel Pickwick burst like another sun from his slumbers; threw open his chamber window, and looked out upon the world beneath.*"—DICKENS.

ALL of us are naturally worshippers of the sun. For a reason difficult to analyze, a bright sun in a blue sky, throwing lights and shades on different parts of the landscape, brings joy to our hearts. It is only in tropical countries that anyone can ever be found who curses the monotony of a hot sun in cloudless skies. Even these men glory in the magic of the sunset. In fact, there is no phenomenon in Nature that arouses more fully than do some sunsets the highest emotions of wonder, awe, and admiration.

In our own country the abundance of cloud gives the widest possible variety to the character and beauty of a sunset. Turner's imagination could not introduce exaggeration into his pictures. To some of us an autumn sunset in the Highlands awakens wonderful flights of imagination. Every autumn, when the trees of the forests, and the heather and bracken of the hills, in the course of one or two weeks, transform our everyday world into a kind of fairyland, it almost seems reasonable to suppose that the fairies had been collecting into their magic pails, from the autumn clouds of sunset, the glorious scarlets, with gold and copper colours, besides the deep purple shadows; and had spent a week or two in painting the trees with glorious colour and laying carpets of russet leaves on the ground. Besides these collectors of the bolder tints from the denser clouds, other fairies would seem to have penetrated westward beyond, through gaps in the streaks of copper and golden clouds, to where you may see the gates of heaven, with the emerald green, turquoise blue, and shining lemon colours. Having painted the trees and herbage, it would seem that they had spread over the mountains a frostlike shimmering by showering upon them the dust of powdered pearls and diamonds. Then they would seem to have opened frail flagons which, for a fortnight, they had been filling with all the rainbows they could collect. And the sun shone, and the banks of scarlet and orange, of gold, russet, and green all laughed in the rainbow air.

Passing from fancies to realities, there is a special and wonderful kind of sunset which the writer has often seen early in the year, off the African coast, during a voyage to the Cape. Then the whole western horizon seems to be blotted out by a continent having a flat, sandy beach and undulations over the generally flat country. A forest may lie in the background, but the surprising features consist of palm-trees with large, well-defined leaves scattered over the shore; while wandering along the beach it is a common thing to see elephants and other animals browsing or drinking from a stream. The scene remains unchanged until darkness closes in.

There is only one kind of *pure* sunset ever to be seen in the world. It is full of scientific interest in giving a spectrum of the sun, and also in supplying valuable information about the upper regions of the terrestrial atmosphere. It occurs on every desert which is at least 1,000 miles from an ocean, for the slightest degree of moisture in the air destroys the purity of the sunset. The writer has often seen the pure sunset in the desert of Gobi. In Upper Egypt it may be seen occasionally. Further south in the Sudan this solemn and marvellous pure sunset occurs regularly every evening. The Karoo regions, and even the alkali deserts of Arizona, have revealed the pure sunset. In all of these places the shadows of your camels and attendants are of a deep purple against the spectrum colours of the western sky, an optical effect which is sometimes to be seen even where no *pure* sunset occurs. The very first symptom of the pure sunset is a rosy colour which tinges the eastern half of the sky horizon away from the sun. It slowly rises as an arch, with the north and south points of the horizon as pivots, upon which the rosy arch rises up in the east a few degrees every minute. When the centre of the arch has risen some 30 degrees above the horizon you are astounded by the most surprising fact that above the rosy arch, over the whole of the firmament, the blue sky is shining as true daylight; while below the arch, within the whole of this sector of the heavens, the sky is black, and the stars are shining brightly.

The arch rises until it is right over you, the rosy colour becoming less prominent. The pivoted arch, separating night from day while you are looking at the region of sunset, rises, from your back and sides, as if the daylight were being cut off by the slowly rising hood of a phaeton in which you are seated. All in front is daylight; all behind is night with stars. The hood passes the zenith and descends to the west until, from end to end, it cuts off an arch, some 30 degrees high, filled with the absolutely pure spectrum-sunset, showing all the colours of the rainbow, violet at the top, passing through layers of blue, green, yellow, and orange until you find, upon the horizon, the more ordinary red glow of sunset. It takes nearly an hour for this western spectrum of the pure sunset to be quite cut off.

By noting the varying direction by compass of the place on the horizon where the sun sets or rises, and the varying altitude that it attains when due south, the sun is distinguished from the fixed stars, each one of which always rises and sets in the same directions, and always attains the same maximum altitude if the observer's latitude is unchanged.

At the two dates March 23 and September 23 the sun rises exactly at 6 a.m. apparent solar time, and sets at 6 p.m. And this is true all over the world in all latitudes and longitudes. At those dates it always rises and sets due east and west of the observer. From

January to June the rising- and setting-points pass daily towards the north in the Northern Hemisphere, and more so in higher latitudes; and from July to December towards the south. Cicero, describing the experiences of Roman legions in North Britain, said: "Fere obtinuit regionem boream oriens sol." It almost rose in the north. In the Southern Hemisphere the opposite rule prevails.

Until after the invention of the telescope in 1610, when Galileo, Fabricius, and Scheiner discovered independently the sun-spots, few had any more knowledge about the sun than the schoolboy who, when asked what he knew about the sun, answered: "It is a long way off; it is round; it is very big; it is very hot; and cats sit in it."

As to the size of the sun and planets, Jupiter is by far the greatest planet. Roughly we may care to memorize the fact that Jupiter is 10 times the diameter of the earth, and the sun nearly 10 times that of Jupiter. The mass of the sun is 1,000 times that of Jupiter, and 330,000 times that of the earth. The earth's diameter is 4 times that of the moon, its mass 80 times. The radius of the earth is about 4,000 miles, the distance to the moon 60 times that, or 240,000 miles. The sun's distance being 93,000,000 miles, we may note that the sun's distance and diameter are both about 400 times those of the moon. Since the distance of the sun in miles is beyond comprehension, let us note it in other ways.

A railway train at 50 miles an hour takes 8 hours from London to Edinburgh. It would take 20 days to go round the Equator, 6 months to travel to the moon, and 220 years to the sun.

A cannon-ball commonly passes over half a mile in a second. At this rate it would take 6 years to reach the sun.

A nerve impulse is transmitted from a burnt finger to the brain at a speed which has been carefully measured. If a new-born baby happened to have an arm so long as to reach the sun, and get its finger burnt there, it would never feel the pain, for the nerve impulse would take 104 years to reach the baby's brain, and then it would be dead.

THE TELESCOPIC SUN

Those of us who rejoice in the possession of Galileo's original publications of his discoveries are surprised to find so much detail and accuracy in the daily drawings he made of the sun-spots. He was able to estimate the period of the sun's rotation on its axis at about a lunar month. The priests of those days held a belief in the "immaculate conception" of the sun, and suggested that the spots were not on the sun; but this opposition soon died down. The dark central *umbra* was noted inside of the less dark but more extended *penumbra* or shaded area enclosing it, sometimes with several umbræ in one penumbra. The size, shape, and duration of spots were found to vary much. Some spots may last only a few days. Sometimes fter a spot has disappeared at the sun's western edge it is never seen again. In other cases, after a fortnight, it reappears on the eastern edge. The longest duration of a spot was 18 months in 1840 and 1841. The largest spot ever photographed was in January, 1926, over 50,000 miles across.

Galileo also discovered the *faculae* or bright-spotted areas, seen all over the sun's surface, but best in the neighbourhood of spots. Seven great fundamental discoveries about sun-spots have been made by telescopic observations since Galileo's time.

1. Little advance over the first discoveries was made until 1769, when Alexander Wilson, of Glasgow, described a movement he had often noticed of the dark umbra over the outer penumbra during the transit of a spot across the sun's surface. It seemed that the spot must be a saucer-shaped hollow on the sun's surface, the base being the black umbra, the sloping sides the penumbra. When such a spot is close to the sun's edge he found the saucer-hollow to be tilted, and the part of the penumbra nearest the sun's centre could not be seen because of the sloping sides of the saucer.

In the photographs now taken of the sun every day, a spot exactly on the sun's edge is often seen as a decided notch cut out of the solar periphery.

2. Anybody with a small telescope may find much enjoyment by drawing each day the shape and position of the spots. It was by the steady pursuit of this hobby that R. C. Carrington produced his book of sun-pictures between the years 1853 and 1861. Thus he found the sun's axis of rotation to be inclined 7½ degrees from the pole of the earth's orbit. But his great fundamental discovery was this: *Spots near the*

Equator complete their revolution more quickly than those in higher latitudes. Spots are seldom seen near the Equator, and never at higher latitudes than 50 degrees, as Sir John Herschel had discovered. A more modern method of measuring the rotation period of the sun's surface, independently of spots, has thoroughly confirmed Carrington, and has extended his results to give the rotation periods at latitudes 0, 30, 60, and 80 degrees as being 24·46, 26·43, 29·63, and 30·56 days. This wonderful discovery fixes our ideas of the sun. It cannot rotate thus as a solid body, and, whether it be liquid or gaseous, there must be a perfectly enormous expenditure of energy to maintain these differences of velocity in spite of the liquid or gaseous friction.

3. The next discovery of overwhelming importance was made by Schwabe, of Dessau, who began a systematic study of the solar surface in 1826, noticing the number of spots to be seen in a month or a year. He reached the conclusion, in 1843 and 1851, that every 10 or 11 years this number of spots attains a maximum. This law, though not perfectly regular, has been thoroughly established by subsequent research, and also by the examination of older data. This *sun-spot period* of about 11 years has been more fruitful of results than any discovery in solar physics.

4. In 1851, Lamont, a Scotsman at Munich, announced a similar period in the daily range of magnetic declination. (A compass needle points roughly to the north, but changes of direction can

be detected, and these have a varying "daily range.") Sometimes these changes are violent and prolonged as "magnetic storms."

In 1852 Sir Edward Sabine extended Lamont's discovery by proving an eleven-year period in the magnetic storms that affect all three magnetic elements of direction and intensity from concordant observations in England, Australia, and Canada. The same law was independently discovered by Wolf at Zürich, and by Gauthier at Geneva.

This connection between frequency of sun-spots and terrestrial magnetism is now thoroughly established. Great outbursts of sun-spots are often accompanied by magnetic storms. The passage of a large spot over the central part of the sun is often the signal for a magnetic storm on our earth.

Maunder finds that magnetic storms often recur at intervals of 4 weeks, the period of the sun's rotation, when the same bit of the sun's surface must be in the central meridian of the sun.

5. Furthermore, a similar connection between auroræ and the periods of sun-spot and magnetic storm frequency has been established. In fact, the aurora borealis and magnetic disturbances occur simultaneously.

6. Another rule about sun-spots, of primary importance, was discovered by Spoerer. The 11-year rise and fall in number of sun-spots does not go on simultaneously in all solar latitudes. Each new cycle begins with spots in high latitudes. As their number increases the average latitude becomes less. At the

end of the cycle they average a still lower latitude, nearer to the Equator than at any other time. And then that cycle ends. A very remarkable feature of these cycles is that before one cycle has come to an end in low latitudes, the next cycle has begun to show itself in high latitudes.

7. Finally, during any total eclipse of the sun, a bright corona, which is a solar appendage, is seen round the black moon, extending often over many diameters of the moon. The shape varies in different eclipses. At times of sun-spot maximum the corona is of a fairly round form, concentric with the moon. At times of sun-spot minimum, on the other hand, the sun's polar regions are deserted except for spiky jets, while the main bright corona extends in long Equatorial wings.

These are the fundamental facts derived from telescopic research that govern sun-spots. To these must be added presently some very important facts derived from spectroscopic research.

The eleven-year period in the frequency of sun-spots has given rise to numerous attempts at finding eleven-year periods in terrestrial events, such as storms in the Indian Ocean, heights of Nile floods, famines in India, vintage years of fine German wines, freezing dates of Siberian rivers. Nothing very definite has transpired. But the solar heat of radiation is found to vary from year to year; and the opinion prevails that in maximum sun-spot years the solar energy of radiation is increased.

If, as is generally believed, the sun's constitution is gaseous, although having a mean density 40 per cent. greater than water, it is very remarkable that it presents in the telescope a very sharp boundary to its gaseous mass. This boundary is called the "*photosphere*," the layer which is the principal source of solar light and heat. This visible surface has always been a subject of great interest; but a very difficult one to study, chiefly because of the rapid changes in appearance of the so-called willow-leaves or rice-grains forming the groundwork. These minute elongated bodies can be seen only under the very best observing conditions, and were discovered by that remarkable Scotsman, James Nasmyth, the engineer of steam-hammer fame, who, like W. Herschel and other great astronomers, was the maker of his own telescopes.

The study of these rice-grains on the solar surface is rendered far more complete by the application of photography. Solar photography was first brought to a high state of perfection by Mr. Warren de la Rue. It was he who produced the photoheliographs which we used in the transit of Venus in 1874, before rapid dry plates had been invented, and which are still in use.

Janssen succeeded in producing some beautiful photographs of the rice-grain structure at Meudon, near Paris. Each grain has a diameter of about a second of arc. The rapid transformations and movements of these rice-grains would lead to a great advance in our knowledge of solar physics if they were thoroughly and continuously studied. This seemed impossible owing to the rapid movements and changes of shapes.

Only one man has ventured successfully upon this promising but difficult line of research. This was Hansky, an astronomer of the Russian Observatory at Pulkowo. He introduced a scheme of photography which might almost be called solar cinema films. He took photographs of the sun at intervals of 15 or 30 minutes. He then enlarged selected portions of the pictures 200 times, corresponding to a solar disc of 7 or 8 feet diameter. In these enlarged pictures he was able to identify individual rice-grains, and to trace the movements and changes of shape and brightness of each one. Some of the granules become larger or smaller. Some seem to rise out of a mist, as it were, and to become clearer. Others grow feebler. Some got split into two. Some were seen to be rotated through a right angle in a minute or less, although each grain may be as large as Great Britain.

Generally they move in groups of very different and varying velocities up to some 25 miles a second. These movements seem to have definite relation to any sun-spots in the locality. This is all, and it is a great deal, that Hansky accomplished, foreshadowing great possibility of fertile discovery. And then he died. Since then no one has had the energy and devotion required to continue this wonderful research.

THE SPECTROSCOPIC SUN

Sir Isaac Newton's marvellous power of divining the right course to be followed, out of several alternative courses, for arriving at truth, and his unexampled power of rapidly expounding the developments of a theory so discovered, were only equalled by his, at that time, unequalled, manipulative, and experimental skill in ascertaining the true facts.

The former powers are best shown in the *Principia* (1686-1687), the latter in his *Optics* (1704).

His great discovery in optics was that the white light of the sun is composite, made up of many colours. He devised means for splitting up sunlight into its constituent colours, and also of recombining all of them into pure white light.

If a vertical slit be made in a window-shutter and sunlight admitted through this slit into the room, Newton found that if he examined the slit through two sides of a piece of glass which are parallel (like any sheet of glass) he saw the slit in the same direction as before, of the same width, and the light coming through was white as before. But he also found that, if the two faces of glass through which he looked were not parallel, but inclined to each other at an angle, he saw the slit in a new place, shifted to one side, wider than before, and coloured red at one side and blue or violet at the other side. This coloured band is the solar "*spectrum*."

If the sides be largely inclined this becomes very marked. If, for example, the glass be three-sided with equal sides, like the old-fashioned chandelier drops or prisms, then the sunlight, after passing through the slit, is deflected something like 30 degrees while passing through two faces of the prism. The slit now looks wider, drawn out into a coloured ribbon, red at the side nearest to the slit, violet at the other end. Newton identified the colours he saw as seven in number, red, orange, yellow, green, blue, indigo, and violet. It was as if he was looking at 7 slits of 7 different colours. In this experiment the slit was not extremely narrow. So the seven colours (if there were only seven) overlapped one another. As a matter of fact, Newton's discovery was made with a hole one-third inch diameter in place of the slit.

Later a very narrow slit was used, and was examined by lenses which magnified it. It then became clear that the number of slits of different colour which were seen, even if the eye would not perceive the different shades of colour, was practically infinite, if the slit could be made narrow enough to prevent the overlapping. The combination of slit, lenses, and prism or prisms was then called a "*spectroscope.*"

It was found that in the solar spectrum some colours were missing, or so enfeebled as to look like dark lines crossing the bright spectrum. With very refined optical parts in a special kind of spectroscope, Rowland, of Baltimore, counted 20,000 of these dark lines. Now the number is greatly increased. These lines, in the band of light called the *spectrum*, can be photographed. And the exact position of each missing or weakened line can be accurately measured, and so can be identified in the light coming from other sources of light besides the sun.

Each chemical element found on our planet, when vaporized at intense heat as by an electric spark, and examined with a spectroscope, gives off a limited, though large, number of *bright* pictures of the slit differing in colour, instead of *dark* lines, on a continuous spectrum of colours, as seen on the sun.

In a vast number of cases the spectrum of some chemical element used in our laboratory has all of its lines (sometimes numbering thousands) reproduced in the solar spectrum as dark lines in precisely the same position. Thus, we come to know of the existence in the sun of about half of the elements known to chemists as being found on our planet. Possibly the other elements may all be there, though hitherto undiscovered.

This wonderful power now possessed by astronomers of making a chemical analysis of the materials existing in the sun, stars, and nebulæ at incalculable distances from us, opens up a new world for discovery. But this does not end the information gained from a spectrum, and a new science called "*astrophysics*" has come into being. We are still, and shall be for ages, trying to discover many new truths that the spectrum of any element can tell us. A few of these may now be mentioned.

1. The eastern side of the rotating sun is approaching us. This approaching is found, in accordance with theory, to shift slightly the exact position of all the spectrum lines towards the violet end of the spectrum. The western side is receding, and a similar shift is found towards the red. In this way we can actually measure the rate (in miles per second) at

which one part of the sun, or a star, is receding from or approaching us.

This shortly stated fact concerning "*radial velocity*," or velocity in our line of sight, gives more value to the spectroscope as an aid to pure astronomy than any of its other developments. It enables us to get very accurately the period of rotation of the sun in latitudes where spots are never seen. It gives a very accurate means for finding the distance of the sun from our planet. It has detected rotation on an axis in stars like Algol. It detects double stars revolving round each other, inseparable in the telescope. It tells us a great deal about the motions of the stars in space of which a telescope can tell us nothing. It detects whirls of glowing hydrogen in "new stars." It enables us to discover the masses of some stars. In fact, the power of measuring radial velocities by a shift in the position of spectrum lines has countless applications among all stars and in every department of astronomy. *A shift of lines towards violet means approach; towards red means recession.*

2. Information is also obtained about the gas-pressure of the sun's atmosphere, or any other place where spectrum lines originate. This is indicated by a widening of the lines. Thus, we have learned that, at that level in the sun's atmosphere where the white light of the sun is absorbed by atoms of iron, hydrogen, sodium, etc., the pressure is very much less than the 30 inches of a barometer, which we find on the earth's surface.

3. The relative intensity of certain lines in the

spectra of different stars varies considerably. This phenomenon has been reproduced in the laboratory, and is found to give an indication of a star's temperature. Another indication of the surface temperature of the sun and stars comes from different ratios, in different sources of light, of selected portions of the continuous spectrum.

4. To give one more instance, it has been discovered by delicate laboratory experiments that when we are examining a spectrum line from some electric spark, its whole character is changed if the spark is in the neighbourhood of a strong magnet. The lines may be split up into doublets or triplets, and the light is what is called "*polarized*." These effects in the laboratory have been so well experimented on that the magnetic conditions in the place where any source of light may be, can be told with a great degree of definiteness.

We cannot help being almost spellbound even by these few examples of what a spectrum tells us. They are only a beginning. For ages to come chemists must continue to work on spectra in their laboratories, while astronomers are doing the same with stellar spectra in their observatories, before we can hope to know more than the elementary principles of spectrum analysis. Already astronomers have thus helped chemists, and received a like return of greater knowledge from chemists.

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A great deal of knowledge about the sun's surface followed Lockyer's discoveries about the spectrum of sun-spots. In the focus of a large telescope place a sheet of paper or metal and you see a picture of the sun just as you would see a landscape on the ground-glass of a photographic camera. Lockyer placed the slit of his spectroscope there, and adjusted its position so that a sun-spot fell on the slit. He found that its spectrum differed a little from what is seen on the other parts of the solar surface. Without going into great detail it may be said that he found good reason for inferring that the temperature of a sun-spot is much lower. In this spectrum we actually find the lines that indicate *titanium oxide,* which generally is only found in stars of the lowest temperatures, half the temperature of the solar surface.

Lockyer found also that the spectrum lines were so shifted as to show gigantic up-and-down movements in the atmosphere above a sun-spot. These and subsequent researches have led astronomers to the conclusion that enormously hot vapours rise through the photosphere into the upper atmosphere, where they expand and get colder, and sink to a lower level where the spots are formed.

The estimates of temperature on the sun now promulgated are so startling that they deserve mention. The highest temperature we can attain in the laboratory is from carbon in the electric arc, and is about 4,000 degrees. The sun's surface generally has a temperature of 6,000 degrees. The titanium oxide spectrum lines in sun-spots indicate 3,000 degrees. Meanwhile, we are told by the theorists that the temperature inside the sun is 30 or 40 million degrees.

There is another wonderful application of the spectroscope to the solar atmosphere relating to the metal *calcium*. Take one particular line, a broad line in the solar spectrum generally indicated by the letter K. This line takes on three different characters, according to the temperature and gaseous pressure. At low levels in the sun's atmosphere it is a broad, *dark* line. Higher up in the atmosphere it is a narrower line of great *brightness*. Still higher up a *dark* line bisects this. Thus, if we look through all three layers, we see a dark absorption line of considerable breadth, with a central narrower bright emission line, bisected by a fine, central, dark absorption line.

It is possible to place a spectroscope slit on one or other of these three parts, and so to study the calcium clouds in the sun's atmosphere at three different levels.

This kind of investigation leads, naturally, to a short account of a wonderful form of spectroscope called the "*spectroheliograph.*" It is a marvel of mechanical and optical construction, and has given us results of the most surprising character concerning the surface and atmosphere of the sun.

This new instrument was first made by Deslandres in France, and by Hale in the U.S.A., to enable us to take a photograph of the sun *all in one colour*, some particular colour (distinctive, let us say, of hydrogen or calcium), which is one of the images of the slit seen in a spectroscope attached to a telescope pointed to the sun. Let us call that slit the *first slit* of the new apparatus. It is in the focus of the telescope, where a picture of the sun is formed, and it allows to pass through it only the light from that part of the sun's circular image which lies on the straight line, the first slit. The ordinary spectroscope, when applied to this telescope, gives a spectrum of that particular straight-line-section of the sun. The new device now comes in. On this spectrum choose any one definite colour belonging to any chemical element. Place a *second slit* there to allow only that colour to pass. A photographic camera enables that one section of the sun to be photographed in the one selected colour. If now, by means of any mechanical appliance, the two slits are moved simultaneously, the one over the picture of the sun, and the other in front of the camera, a photograph of the sun, made up of innumerable straight-line sections of its disc, is reproduced on the photographic plate, using only the one colour selected for examination.

In some such manner we can take photographs of the sun in calcium light at three different levels in its atmosphere. Or we may photograph the distribution of hydrogen clouds over the sun's surface. All of these separate photographs of the sun show very different shapes of hydrogen or calcium clouds, with a very marked relationship to the sun-spots.

In this way of working progress was very rapid. Since 1908, however, it has been possible to photograph certain hydrogen clouds that are very high up in the solar atmosphere. It is from these photographs that the most surprising results have been attained, shedding a new light upon our knowledge of sun-spots.

It had been expected that the new exploration would have disclosed currents in the sun's atmosphere like those familiar to us in terrestrial meteorology. The calcium "*flocculi*" (as they are called) revealed the existence of no such currents; and it was not until 1908 that any were discovered, when hydrogen in the upper regions of the solar atmosphere could be photographed, owing to the production of a photographic plate sensitive to red. The second slit has to be adjusted on a certain one of the hydrogen lines which is red.

These hydrogen flocculi are located over the sun-spots, and their forms proved that "*all sun-spots are vortical in Nature, and are probably analogous to terrestrial cyclones or tornadoes*" (George Hale). The photographs from which this deduction has been made are of surpassing interest. It happens that a certain discontinuity in the hydrogen vapour enables us actually to see in black and white the whirlwind form. Spiral arms, more or less complete, are seen radiating out from the central, black, round spot. The general drift of the spiral arms is clearly in *one* direction of rotation. And when, as is common, there is a pair of whirlwind spots, the picture of these rotating in opposite directions is most suggestive.

But this is not all. After this great discovery had been made, George Hale, at Mount Wilson Observatory, California, followed it up by the astounding discovery that within those vortical tornadoes, all the symptoms of a magnetic field, which had been so completely investigated in the laboratory, were perfectly reproduced. Hale found the duplication or triplication of a spectrum line and its polarization so certainly that he was able to state positively — and this statement has never been challenged—that magnetic polarity is found near sun-spots, on the general surface of the sun, and particularly on the cyclones which are related to the spots. Since the year of these discoveries, 1908, continuous observations have been made upon the magnetic condition of all parts of the sun.

A sun-spot is often double, with opposite directions of rotation, and with opposite magnetic polarity in the two vortices. The leading spot is the primary one of the pair, and its polarity, N. or S., seems to be quite constant. One of the pair may be the first to disappear before the other one, and in such cases Hale has found the magnetic polarity to continue after the spot has disappeared.

He has gone further, and is able to locate the second spot of a pair by the magnetic field *before it is visible in the telescope;* and has continued in this way to localize invisible sun-spots.

Perhaps his most remarkable discovery in this connection is that with the birth of a new eleven-year period of sun-spots, their polarity is reversed.

The terrific tornado-like character of sun-spots was disclosed to him in yet another way. A large cloud of hydrogen may hang trembling for several days on the edge of one of these whirlpools, and he has seen these suddenly overcome, and sucked into the spot's whirlpool with a measured velocity of sixty miles a second.

It might be thought that with the vast accumulation of facts—telescopic, photographic, and spectroscopic—about the sun-spots, concerning which a general description has now been given, there ought to emerge a very definite theory of the whole subject, and one that could not be disputed.

All we can say is that solar eruptions seem to be throwing gases into the upper atmosphere, where they cool and fall down to form the spots. This action is accompanied by solar cyclones or tornadoes. But whether these cyclones are originated in the body of the sun or its atmosphere, is not yet ascertained.

THE ECLIPSED SUN

An eclipse of the sun means that the moon is hiding the sun from an observer on our earth. Eclipses are not uncommon, but most of them are only partial eclipses. If the moon be almost exactly in the line of sight from any observer to the centre of the sun, then the sun can be completely blotted out. If the moon, in her monthly orbit, at the new moon, passes a little out of that line, the sun is not totally eclipsed; only a part of it may be cut off by the moon. If, at new moon, the centre of the moon passes our line of sight to the sun, at a greater distance than half a degree, she does not eclipse any part of the sun.

Thus, an eclipse of the sun may be total at one region of the earth's surface, and only partial at other regions. There is a total eclipse of the sun nearly every year, but it is total only over a very limited region of the earth. The last two total eclipses of the sun that were seen anywhere in Great Britain occurred in 1715 and 1724. Now, after about two hundred years, two will be seen in the present century—one on June 29, 1927, the other in 1999. According to the records, Edinburgh has had five total eclipses during the last thirteen hundred years, while London and Dublin have had not more than two. But anyone can see a total eclipse of the sun almost any year if he care to travel to that part of the world where it is total.

A few preliminary words on the cause of total eclipses may now be of general interest. The moon shines because one-half of it receives the sun's light. The other half is dark. The sun's diameter is about 400 times that of the moon. So, behind the dark half of the moon lies a conical space unilluminated by the sun. The cone comes to a point, as it fortunately happens, at a distance from the moon very nearly the same as the distance from moon to earth. Hence it follows that, on occasion, a round or oval spot on the earth is in shadow, being a section of the cone with no illumination from the sun, and there the sun is totally eclipsed.

While the moon is circulating round the earth its conical shadow passes over a track on our globe. Thus, from hour to hour, the round shadow-spot on our globe, in the eclipse of 1927, travels from the Atlantic, by Criccieth to Hartlepool, and thence by Norway and Lapland into the Arctic regions north of Siberia. In this case, the track of totality is only 30 miles wide, but it is several thousand miles long.

Every day details of the sun, over its whole surface and round its circumference, are examined and photographed at our great observatories. But there is one great atmospheric appendage surrounding the sun always varying in shape and size, which has never been seen by mortal eye except during a total eclipse. This is a halo called the "*corona*." On ordinary occasions the brilliance of the sun itself obliterates the light from the corona. Even if the sun is hidden by a screen, the illuminated atmosphere above us on the earth overwhelms the light from the corona, as it does the light from the stars, which are all shining as brightly by day as by night.

The wonderful corona can be seen only when the sun and our atmosphere in that direction are darkened by the moon in a total solar eclipse. And the sudden transformation which takes place at the moment when the dark moon has blotted out the last trace of sunlight—a transformation from day, with a sun shining, to night with this glorious, unexpected appendage round the dark moon—provides for every witness of it a sudden thrill, transcending any emotion ever felt by any kind of event happening in the heavens.

The darkness of the sky surrounding this corona of light is sometimes as deep as that of the black central moon. Thus, it often happens that bright stars can be seen with the naked eye. Venus and Mercury, revolving round the sun in orbits smaller than the earth's, can often be seen.

The unassisted eye is also able to detect the "*red prominences*" projected from the surface of the sun. A telescope, even a small one, helps to define their shape.

The contrast of this brilliant illumination to the preceding picture of a round sun shining in the sky is very startling. No longer do we see the everyday sun, but we do see parts of the red layer round it, called the "*chromosphere,*" with outbursts upwards into the white, irregular, feathery corona or upper atmosphere of the sun.

These appendages of the sun can be traced right down almost to the solar surface, from which they seem to spring. This is a remarkable piece of good luck for us inhabitants of the earth. It is due to the wonderful fact that the sun and the moon cover equal spaces in the sky. Or we may say it is due to the fact that the diameter of the sun and its distance from us are, both of them, about 400 times the diameter and distance of the moon, the same multiplier in each case.

If, as is quite possible, our earth is the only planet inhabited by human beings, it is a marvellous coincidence, if we may call it so, that, while we have only one moon (whereas some other planets have nine or ten) it should be exactly the right size for seeing all these wonderful atmospheric appendages of the sun complete in one view.

An inhabitant of the moon, if such there be, in the shadow of our earth, whose diameter is 4 times that of the moon, would not only see the sun blotted out at mid-eclipse, but all of its atmospheric and super-atmospheric appendages would also be blotted out. So it is with Jupiter or Saturn. Some of their moons are so large as to blot out everything round the sun. Others are so small that they would be seen by people on these planets merely as round spots crossing the solar surface.

An eclipse may last about two hours; but it is never total at any one place for longer than a few minutes.

To the astronomer who aims at testing the accuracy of the law of gravitation, the greatest interest attaches to the exact time of the beginning and end of totality. He thus obtains a more accurate knowledge of the moon's position with respect to the sun than he can at any other time. This gives him a greater power to test how far his predictions, founded upon the law of gravitation, agree with, or differ from, the actual truth, and to improve the lunar tables.

To the student of astrophysics a total eclipse is by far the best occasion for studying by telescope, spectroscope, photography, polarizers of light, and photometers, all of the atmospheric appendages of the sun. And it is the only occasion on which he can observe the corona.

No wonder, then, that for a long time past every effort has been made to transport the most powerful instruments to some place on the track of every total eclipse in whatever part of the world it can be seen. These expeditions from the year 1842 till now have increased to a very great extent our knowledge about the constitution of the sun.

As totality approaches, the rough edge of the moon finally allows only " lucid points like a string of bright beads suddenly to be formed, irregular in size and in distance from each other, almost as if caused by the ignition of a fine train of gunpowder." So Francis Baily described them, for the first time, during the annular eclipse of the sun, which he witnessed from Inchbonney, near Jedburgh, in 1836. Ever since they have been called *Baily's beads*.

Before the last curved line of bright sunlight disappears, a direct vision prism is convenient for showing many of the dark lines of the solar spectrum suddenly reversed, and shining bright each in a different colour of the spectrum. This is called the *flash spectrum*. It lasts, generally, only three or four seconds, but by choosing his locality carefully, an astronomer can see it a longer time. It was first seen in the 1870 eclipse by Professor Young, of Princeton, U.S.A.

Now the total phase of the eclipse begins. The sun has disappeared. The great transformation scene is displayed. Our eyes are no longer dazzled either by a bright sun or by an illuminated terrestrial atmosphere round the sun.

The dominant object in the heavens is the corona. It is a marvellous, luminous, feathery structure, at times like the halo round a picture of a saint's head, but far more irregular; and sometimes its shape is different, long streamers of light from the sun's Equator, or curved spikes of light from the North and South Poles of the sun. The outgoing rays, like plumes, often cross one another. The *inner ring* of the corona is the brightest part, giving half of the total light. Its width is only one-tenth of the sun's diameter. Nobody can foretell what the shape will be at any eclipse, except that every eleven years, when there is a maximum number of sun-spots, the corona is more like a halo, and during a sun-spot minimum the Equatorial wings are more marked. These, on rare occasions, reach a great distance. The light from the corona is not steady, but flickers, much resembling the flickering light of the *aurora borealis*. The total illumination from the corona has been estimated from half to nearly one and a half of full moon, and as being the same illumination as from a candle a yard away.

Closer to the sun's surface than the inner corona is the layer of atmosphere, from which eruptions of hydrogen and helium are shot up to form the red prominences of a total eclipse. This layer is called the *Chromosphere*. After we have revelled in the glory of the corona illumination, attention must be given to the "red prominences," which rise out of the chromosphere like flames, eruptions, clouds, arches, etc. A small telescope or field-glasses assist the study of the shapes of these remarkable prominences.

During all this period of totality the professional astronomers are at work with telescope, camera, spectroscope, etc. They have already discovered a method for studying the red prominences in full daylight at any time. The corona alone is never seen except during a total eclipse. They have found that part of its light is reflected sunlight, and that, further, it gives off its own light, showing 16 spectrum lines, and principally a bright green line in spectrum (at 5303°, ångstroms), all indicating a substance, not known on our planet, to which the name "coronium" has been given.

After a short period the total phase of the eclipse is ended too soon for our wishes; the sun regains the supremacy of the sky; and we ourselves return to the ordinary daily routine.

It may well have been, and probably was, after such an occasion, that the Psalmist exclaimed: "The heavens have declared His righteousness, and all the people have seen His glory."

Detailed observation of total eclipses followed Baily's discovery of Baily's beads in the annular eclipse of 1836. His words have already been quoted. In consequence, in 1842, Airy, J. D. Forbes, O. Struve, Schumacher, Arago, Baily, and others scattered themselves over Southern Europe to see what could be seen with a telescope in the total eclipse.

Principal J. D. Forbes then described some of the emotions which people have experienced at the moment when the darkness of totality has engulfed them. He observed that eclipse with Airy from the Superga, near Turin, in an almost cloudless sky, and described the approach of the moon's shadow in these words:

"I perceived in the south-west a black shadow like that of a storm about to break, which obscured the Alps. It was the lunar shadow coming towards us. I confess it was the most terrifying sight I ever saw. As always happens in cases of sudden, silent, unexpected movements, the spectator confounds real and relative motions. I felt almost giddy for a moment, as though the massive building under me bowed on the side of the coming eclipse."

This shadow is now looked for in total eclipses, so it has lost the effect of surprise. Its edge shows flickering *"shadow-bands"* on the ground due to uneven temperatures. In a modern eclipse, January, 1925, Miss Cannon, of Harvard Observatory, at Poughkeepsie, over a snow-bound landscape 12 degrees below zero, gave this account:

"Such a wonderful playground had Nature provided in the snow for this dance of the mystical shadow-band! I saw them clearly about one minute before totality, and they almost took my breath away. They were narrow pencils, dark greyish, and just seemed to flit hither and thither."

Let us now follow Francis Baily, who, in order to prevent all kinds of distraction, locked himself into an upper room in the University of Pavia in Italy during the 1842 eclipse, and set up his Dollond's achromatic at the open window. At last the moment arrived when he became absorbed in the minute examination of the "beads" he had discovered in 1836.

At this stage he tells us: "I was astonished by a tremendous burst of applause from the streets below, and at the same moment I was electrified at the sight of one of the most brilliant and splendid phenomena that can well be imagined. For at that instant the dark body of the moon was suddenly surrounded with a corona, or kind of bright glory similar in shape and relative magnitude to that which painters draw round the heads of saints. Pavia contains many thousand inhabitants, the major part of whom were, at this early hour, walking about the streets and squares or looking out of windows, in order to witness this long-talked-of phenomenon; and when the total obscuration took place, which was *instantaneous,* there was a universal shout from every observer, which 'made the welkin ring,' and for the moment withdrew my attention from the object with which I was immediately occupied. I had, indeed, anticipated the appearance of a luminous circle round the moon during the time of total obscurity; but I did not expect, from any of the accounts of preceding eclipses that I had read, to witness so magnificent an exhibition as that which took place."

He adds some details, and then describes what he says was "the most remarkable circumstance attending the phenomenon, the appearance of *three large protuberances* apparently emanating from the surface of the moon, but evidently forming part of the corona. . . . Their colour was red, tinged with lilac or purple. . . . Their light was perfectly steady, and had none of that flickering or sparkling motion so visible in other parts of the corona."

After the red prominences were thus seen in 1842, the eclipses of 1851 and 1860 were watched by astronomers to study them carefully, and prove their solar, and not lunar, origin.

The total eclipse of 1868, seen in India, was really epoch-making. Janssen applied a spectroscope to the red prominences. They showed the bright-line spectrum due to luminous gases. One yellow line in the spectrum was so bright that Janssen exclaimed: "To-morrow I will observe them in full daylight, without any need for a total eclipse." And he did it; and ever since then the red prominences have been viewed and photographed in this way at many observatories on every clear day.

The flash spectrum of the "reversing layer" was first observed by Young in the 1870 eclipse. He says: "As the moon advances, making narrower and narrower the remaining sickle of the solar disc, the dark lines of the spectrum, for the most part, remain sensibly unchanged. . . . But the moment the sun is hidden, through the whole length of the spectrum, in the red, the green, the violet, the bright lines flash out by hundreds and thousands almost startlingly. . . . The layer seems to be only something under a thousand miles in thickness, and the moon's motion covers it very quickly." Another member of Young's party said: "The phenomenon was so sudden, so unexpected, and so wonderfully beautiful as to force an involuntary exclamation."

From the known facts about auroræ and terrestrial magnetism, we might venture to suggest, for consideration at least, an hypothesis based upon the following facts:

1. Sun-spots become most numerous every eleven years.

2. The corona takes a special form every eleven years.

3. The northern lights, or *aurora borealis,* as seen

in this country, attain a maximum in number at the dates of sun-spot maxima every eleven years.

All of these three kinds of display seem to be connected with a common cause. Where shall we find the connecting link?

The present-day theory of auroræ is that they are electric displays like those we see in a vacuum tube when an electric spark passes through the tube.

The present-day theory asserts further that the source of the auroral electric sparks in our upper atmosphere is the minute electrified particles called *electrons,* which are supposed to form parts of the atoms of all substances.

The present-day theory goes on to say that these electrons are emitted radially from sun-spots. Some go off into space; some strike the upper atmosphere of the earth, causing auroræ and magnetic disturbances. This explains why the number of auroræ seen by us reaches a maximum at the same time that there are most spots on the sun, every eleven years. It also explains several other well-known facts.

If this be so, we can see that those very same electrons must pass first through the upper regions of the sun's atmosphere, producing similar auroræ on the sun, showing radial streamers of faint light, with an uncertain boundary, constantly changing its shape, and with a faint, flickering light.

These features are all very notable in the solar corona. So we are led to adopt, as at least a good working hypothesis, the view that *the corona is* *nothing more nor less than an aurora in the sun's upper atmosphere.*

Summary of Chapter II

The sun is proved to move among the stars when we notice the change with the seasons in the part of our horizon at which the sun rises and sets. Each star always rises and sets in the same place.

The size and distance of the sun can be best realized by analogies.

The telescope reveals dark spots on the sun carried round on its surface in a monthly rotation of the sun. They have black centres, enclosed in a shaded penumbra, and surrounded by spotted, very bright areas called faculæ. The spots often show a hollow saucer-shaped surface. Those near the Equator are carried more quickly round the sun than spots in higher latitudes. The number of spots on the sun's surface varies from year to year with a maximum every eleven years. This sun-spot period is coincident with an eleven-year period in the number of auroræ, and in the observed disturbances in terrestrial magnetism, and other celestial phenomena.

The groundwork of the solar surface, consisting of small fluctuating masses shaped like rice-grains or willow-leaves, can be studied only under the best observing conditions.

The *spectroscope* tells us that most, and perhaps all, of the chemical elements of which the sun is composed are found on our own earth. Its powerful properties tell us also about the movements, temperature, atmospheric pressure and magnetic qualities of the sun's surface and of the spot-regions. It has been so ingeniously applied in the spectroheliograph as to enable us to take a photograph of the sun entirely in any special colour characteristic of any chemical element like hydrogen. It also enables the skilled observer to detect magnetic qualities in the sun, and to prove that sun-spots are vortical whorls, like cyclones in our atmosphere.

The conclusions about the nature of the sun, derived from daily telescopic and spectroscopic evidence, besides the important special evidence obtained during the occurrence of total solar eclipses, are these:

The sun is a gaseous mass compressed by its own gravitation-attraction, to a mean density of nearly 1½ times the density of water. Its temperature in the interior being estimated at about 30 or 40 million degrees.

This gaseous sphere diminishes in density to very low pressures at the sun's exterior. It has, however, a fairly sharp, visible boundary, defined as being that spherical surface which separates the dense gases, giving a continuous spectrum, from the rarer parts above, which give the spectra of gases. This is the only boundary that we can assign to the sun's body. It is a spherical surface, and is called the *photosphere*.

The layers of atmosphere above the photosphere, to a depth of a few hundred miles, absorb and scatter the light of certain colours, and so produce dark lines in the spectrum. This is the *reversing layer* seen as a spectrum of bright lines in the *flash spectrum* of a total eclipse. The temperature here is 6,000 degrees.

Still higher, this reversing layer merges into the layer of lighter gases, out of which the *red prominences* of different kinds are shot upwards.

This layer of atmosphere is called the *chromosphere*. It is several thousand miles deep. Masses of this luminous gas are often shot up hundreds of thousands of miles above the photosphere.

In total eclipses alone we discover, further, an outer envelope of very great height, of irregular form and outline. This is called the *corona*. Its light is partly reflected sunlight, but it contains a luminous gas, *coronium*, not known in our laboratories.

Finally, some astronomers include, as a solar appendage, the zodiacal light as a belt extending from the sun on the plane of the ecliptic, composed, perhaps, of meteoric dust.

These seem to be established facts.

The present theory of sun-spots is that gases are erupted into the upper atmosphere, are cooled, and fall with vortical movements to form the dark sun-spots.

CHAPTER III

THE MOON

At night the moon attracts our attention more than all the stars. Planets and remarkable stars may, no doubt, be sought for by us with a greater curiosity, but it is the moon that generally rivets our attention in the first outlook on a starry night.

The moon is invisible for several nights about the time of new moon, when, without being visible, she passes the line of our sight towards the sun. The first sight of the young moon, about two days old, claims our attention as a narrow crescent at sunset, and is welcomed, after the many moonless evenings, by people of all classes. We can hardly wonder if the more ignorant have connected the conditions of this monthly reappearance with some irrational hope, fear, or omen.

During the writer's boyhood there was no occasion when his artistic emotion as well as scientific interest was stirred more than during the periods when he was a visitor to the Astronomer Royal at Greenwich Observatory. For the brilliant sunsets in the west, seen from the drawing-room, over the London haze with its deep red colour, and the horizontal bars of gold near the sun, had as a foreground at some seasons the graceful spire of the Roman Catholic Church on Croom's Hill, rising upright from out the trees which outline the steep hill. Then we noticed that, on two nights of the year, the ruddy sun sank so as to fill centrally the dome of St. Paul's.

On such an evening when the delicate spire was crowned by a two-days-old crescent moon, with its bright side always pointing directly to the sun, the scene was perfect. The Astronomer Royal would leave his calculations and come to the window to enjoy once more such a sunset, and was always uplifted by the old but ever-glorious picture. We envied the Miss Airys, who, on every occasion of this sort, made a charming water-colour sketch of the scene, always the same, always different.

Returning to the moon, we youngsters noticed, among many things, that on each following night she did not reach the region of the spire-top till 48 minutes later. At this rate a complete revolution of the moon round the earth from new moon to new moon is got, roughly, by dividing 24 hours, or 1,440 minutes, by 48, giving 30 days. We often noticed the dark part of the crescent moon, illuminated, not directly by the sun, but only by the dull light reflected to it from the sun-lit half of the earth; the old moon in the new moon's arms.

We noticed the change of shape each night as the moon receded from the sun. And it was always clear that a stick, held up at right angles to the lines joining the moon's horns, points to the sun, the source of the one-sided illumination of the moon's ball-shaped surface.

We noticed the crescent grow thicker each night, until, at the age of 7½ days after birth at new moon, the moon is a complete semicircle. This shape occurs at the "first quarter." Also at the "last quarter" at the age of 22½ days. At these two dates of first and last quarters we could fix within a few hours the time when the boundary of light and shade on the semicircular moon was a straight line. We could not fix with any exactness the time of full moon (age = 15 days). And at new moon (age = 0) the moon is invisible.

Thus it is easily possible to note the time taken from first quarter to first quarter, or from last quarter to last quarter, as 29½ days, and this is the moon's period for going round the earth with respect to the sun. Astronomers using a slightly different kind of method, from observations thousands of lunar months apart, find the period to be 29·530588715 days. For many purposes, if we take the moon's period of revolution round the earth at 30 days, we shall be near enough.

The age of the moon regulates the hours when we need no lantern to go home with in the country. A knowledge of the moon's age, from which we can make a good guess as to the times of rising and setting, tells the yachtsman or fisherman at what hour it will be easy to make a landing. If you propose spending an evening with your telescope on the stars, you avoid any night when the moon is near the full (fifteen days old). It is often good to know when to expect spring-tides, when the moon is new or full. In fact, there is no need to labour the point that even in peace-time, when there are no air-raids, we often want to know the age of the moon.

Fortunately there is a rough-and-ready rule, easily remembered, by which the moon's age at any date can be found.

Here is the rule: There are three numbers which have to be added together to give the moon's age. If ever the sum exceeds 30, the moon's greatest age, you subtract 30. The remainder is the moon's age at the given dates.

The three numbers are called the year-number, the month-number, and the day-number.

1. *The day-number* is simply the day of the month.

2. *The year-number* in 1911 was 0. For each year after 1911 you add 11. When the number exceeds 30 you always subtract 30. For example, take the year 1925; that is 14 years after 1911; 14 elevens is 154, greater than 30. We have to subtract 5 thirties (or 150). The remainder is 4, the year-number for 1925. So it is 15 for 1926, 26 for 1927, 7 for 1928, 18 for 1929, 29 for 1930. (The rule has been very accurate for fifty years. Adding 1 to the year-number will make it more accurate for the next fifty years. Then the last digit of the year itself is that of the year-number.)

3. *The month-number* is best remembered thus: Write on one line the initial letter of each month, equally spaced, and below each month the following *month-numbers:*

J	F	M	A	M	J	H	A	S	O	N	D
0	2	0	2	2	4	4	6	7	8	9	10

After reading several times the row of numbers, *in pairs,* their sequence is easily remembered.

As an example, take June 29, 1927.

1927 year-number + 1 day ... = 27
June month-number ... ... = 4
Twenty-ninth day of the month = 29

Sum = 60

Deducting 30 twice, the remainder is 0, the age of the moon. June 29, 1927, is new moon.

At this early stage many a youngster notices that in winter the full moon is as high up in the sky as the sun is in summer, and in summer it rises no higher above the horizon than the sun does in winter. In our latitudes this height is only one-fourth of what it is in summer. All stars except planets rise to the same height in the sky every night of the year. Also they always begin to rise over the same farmhouse or tree or mountain peak.

The moon, on the other hand, rises over a slightly different locality on our horizon night after night. It completes its rising and setting places on the eastern and western horizon to and fro once a month, just as the sun does once a year. These are a few of the notable things about the moon which any boy may discover at an early age.

Thus, again, it does not take long to notice the fact that the moon always presents to our inspection the same half of her spherical form. We can always recognize the same markings—the dark eyebrows of the man in the moon, especially his left eye, which you feel sure is winking, and his smudged mouth, while the tip of his nose is always seen near the middle of the full moon. No person has ever seen the other side of the moon. This means that the moon rotates on an axis, as the earth does, but in exactly the same time as it takes to go round the earth. Some people say the moon is not rotating, because if you tie a ball to a string and whirl it round your head, you always see the same face of the ball. This argument is ingenious, but quite wrong, from a failure to define accurately the word "rotate." The equality in time of rotation and revolution by the moon is supposed to be due to the friction of tides on the moon that are caused by the earth's attraction, just as it is nearly certain that the earth's rotation is being very slowly diminished by the tides produced upon it by the moon.

This examination of the moon's physiognomy leads naturally to an examination of the moon's surface with a small telescope. For there is no object in the heavens that offers more beauty and wonder to us than the details of the moon's surface markings in her different phases. Every addition to the power of the telescope increases the wonder of this new world. There is much pleasure in comparing the moon's surface with a map of the moon, and learning the names of the different features—hills, hollows, plains—all very different from what we see upon the earth. Oceans, continents, great mountain ranges and lakes are all absent, and we feel that we are looking upon a dead world.

Looking through a telescope at the full moon, it is easy to see that the general outlook is upon two types of scenery. Around the poles, especially at the southern pole, the surface is white as snow, but round one great-circle on the moon, near to, but not actually on, its equator, the surface is black as the ice on a newly swept curling-pond. There is, however, a further feature of the most extraordinary nature. In the southern snow-cap, one of the largest of those white, ring-shaped mountains, usually called "craters," is called Tycho. Its position can be easily noted, because that point is the centre of a star-shaped set of wonderfully radiating streaks or cracks, reminding us of the star-shaped cracks on a frozen pond when a skater has sat down too suddenly and has cracked the ice. These " Tycho streaks " extend to great distances, almost right across the whole visible surface of the moon, and are most distinct at the full moon.

These are the three things that strike the eye in the first look through a telescope at the full moon: the great surfaces white as snow, the black belt like clean ice, and the streaks like ice-cracks.

The whole of the white regions are broken up and disturbed, and covered with lunar craters, whose shapes can be best examined when the moon is not nearly full.

The zone of black regions is one whose pole would come somewhere near to the crater Tycho, the centre of the streaks. The whole of this zone has the appearance of a succession of large, calm, level, and generally circular seas, separated from each other by white, rough boundaries. A simple glance establishes the circular form of some of these—the Sea of Crises, the Sea of Nectar, the Sea of Serenity, and the Sea of Showers. They have been called seas as the ring mountains have been called craters—without good reason from terrestrial analogies.

The moon's temperature is far too low to permit the presence of liquid water. Nor is there any air; at least, Bessel proved that its density cannot exceed the nine hundredth part of our own atmosphere.

When we look with a telescope at the moon in the first quarter, or in any phase except full moon, our attention is engrossed with wonder at the forms of the lunar craters in the snow-white regions. In fact, it is probably true that to many amateur astronomers there is no more attractive object in the heavens than the weird shapes of those craters which lie near the boundary between the illuminated half of the moon and the half that is in shadow. It is, then, possible to judge, from the shadows cast by the sun, how high, steep, and rugged are the walls of these craters—in some cases miles high.

The shadow of the crags on one side falls upon the floor of the crater. Often it happens that the sunlight reaches only the summits of the peaks inside the crater, and these appear as bright spots on a dark, unseen background.

The most common features of these craters are the flat floor, level with the general surface of the moon, the rings of crags enclosing it, and a hill or cone rising out from the centre of the floor. The variations from this type are innumerable. They vary much in diameter and in the heights both of the crags and the central hill. Every stage of transition from the typical form can be traced until we find, in the whitest regions near Tycho, mere holes pierced in the surface, showing no floor, no central cone, no surrounding ridge.

In some regions near to Tycho and the south pole the craters are unusually abundant, and so close together that the enclosing ring of one may be deflected or obliterated at one side by another encroaching crater.

Those who have not the opportunity of studying these marvels through a telescope can obtain almost as much information by securing copies of the photographs from the great observatories of the world, in which every detail can be examined. But, best of all, they can look at the splendid atlas of the moon by the French astronomers, Puiseux and Loewy, who have published copies of their beautiful negatives, enlarged so that the whole diameter of the moon is six feet across.

Those who look at these large maps may see a startling optical illusion. You lay out the map on a table with the window, say, on your right side. Turning the map round on the table, you can find a position where the window is in the direction where the sun was when the photograph was taken. You then see, by their shadows, the normal form of the craters, ring-ridges, floor, and cone. Now turn the map through 180 degrees to the opposite position. The light falls on the plan in the wrong direction. The hills become hollows and the hollows mounds, and it is difficult to believe that this is not the real condition of affairs.

Everybody has an affection for the moon. The points of view vary when regarded by the astronomer, the philosopher, the mathematician, the poet, the lover, the artist, or the practical man. All are beautiful and as diverse and varied as her own phases.

Reborn every month, invisible at birth, she first appears as a delicate crescent, two days old since new moon, in the amber light of sunset, a reincarnation grasping in her arms the shade of her prior existence, the old moon in the new moon's arms. At the age of seven or eight days her face is a sharply cut half-circle of white. Then she takes on that curious form "gibbous," until at the age of fifteen days she dominates everything in heaven and on earth, as the full moon, queen of night, round, bright, and glorious. Her declining days have an air of dissipation and decadence when exposed to our gaze during the forenoon hours, until she is lost in a beautiful second childhood before the hour of sunrise, and dies at the age of thirty days, to be again reborn.

But it is not only in her changing phases that the moon is an object of interest to the average man. There is nothing else in Nature quite like the strong shadows cast upon our path by the moon. There is nothing quite like its reflections from the ripples of a lake, or from the waves of the sea on a long voyage. When we watch the couples on deck expressing these thoughts to each other, we then learn something of the influence of the moon on human destinies.

On a night of full moon the spirit is uplifted, and many there are who repeat to themselves the words of Lorenzo:

"The moon shines bright: in such a night as this,
When the sweet wind did quietly kiss the trees,
And they did make no noise,—in such a night,"

was the soul of many a hero stirred to start upon an historic adventure which is now an epic poem. On such a night, in the lives of most of us, did some event occur that now recalls some thrilling incident of our youthful enthusiasms.

The moon is an inspirer of memories to everyone. Furthermore, she is a true guide to the traveller, a lamp of hope to the way-worn, and of safety to the mariner, an inspiration to the poet and the musician, and—marvellous gift!—she is the one connecting bond with his own people to the exile or prisoner in distant lands, the one recognizable object of common delight to him and them. The present writer has known this to be true ever since, over fifty years ago, he heard this plaintive utterance, on the shores of Lake Baikal, from the lips of a Scottish girl, herself an exile for life in the wilds of Siberia.

In another mood our thoughts about the moon turn to the tides, raised and driven by the moon's force of gravitation, with which our luminous attendant sweeps and scours the estuaries and ocean shores, as a scavenger, safeguarding the health of millions.

The first time we point a good telescope or field-glass on the moon a most unexpected new pleasure is evoked, in examining the strange formations of its topography, the queer shapes, and the contrasts of black and white, under the different angles of illumination from the sun as the moon goes on from night to night with a changing direction of exposure to the sun's illuminating beams.

Finally, we are attracted by the intellectual problems about the moon's motion round the earth.

Eclipses of the sun and moon can be seen only when new or full moon occurs at or about the date when the moon in her inclined orbit cuts the ecliptic. An eclipse of the sun may be total as seen from some parts of the earth, and more or less partial from other parts. An eclipse of the moon is the same, in all its phases, when seen from any part of the world where the moon is above the horizon.

Eclipses generally, and total eclipses of the sun especially, have attracted so much attention and caused so much alarm that we have many records of eclipses in the ancient days of China, Babylon, and other countries. These ancient records have given to modern astronomers accurate information about the relative positions of sun and moon at certain dates. By the help of these ancient records astronomers have been enabled to draw most valuable conclusions as to variation in the mean motion of the moon, and in the speed of the earth's rotation, during the thousands of years since the records were made.

It is interesting to note the conditions under which an eclipse of the sun may be total or annular as seen from a place on the earth which lies on the central line of the moon's conical shadow, wherein the sun must be quite invisible.

The eclipse is total over one region of the earth if the point of the moon's conical shadow reaches as far as the earth's surface. The eclipse is annular if the point of the moon's shadow-cone falls short of the earth's surface.

The length of this shadow-cone varies from 228,120 miles to 235,700 miles. The mean distance from the moon's centre to the earth's surface is 234,900 miles. But this may vary up or down by some 10,000 miles, as the moon's distance changes in her elliptic orbit round the earth.

These figures exhibit clearly our extraordinary good fortune in having a moon of such a size and at such a distance as to make a screen of the exact size requisite to shield all of the solar surface and no more.

Ever since Sir Isaac Newton, in 1687, gave us a knowledge of the force of universal gravitation, people, very properly, have been trying to pick holes in the theory when they can find disagreements between observations of the moon's place among the stars and her place as predicted from Newton's law.

The moon was generally chosen as the suspect rather than the planets, because its smooth path round the earth is seriously deflected by the very powerful attractions of the massive sun. In every such attack upon Newton's law the error was found to lie with the mathematicians, who had omitted something in their calculations for predicting the place of the moon among the stars.

At present there are several theories of the moon, though none has gained general acceptance, still less proof. On our own earth, geologists refer us to denudation, volcanoes, and glacier action as being responsible for the mountains and valleys, the continents, and oceans. On the moon the surface features are totally different, and the temperature is so terribly low that denudation by water is out of the question.

The old idea, still held by some, was that the ring-shaped craters are really volcanic craters like those on our own earth. Now, however, those who are best acquainted with our own volcanoes find that, in essential features, there is a total dissimilarity, and the volcanic theory is in abeyance.

Other people have suggested that the craters were formed by huge ærolites falling from the sky and digging themselves into the level surface, throwing up the excavated material in a ring. The shell-holes in France during the Great War suggested this explanation to many minds. There is, moreover, in Arizona a huge pit resembling a lunar crater, and large, massive blocks have been found in and around the region, possessing all the characteristics of the ærolites which have been seen to fall on to the earth's surface from planetary and stellar space. Nevertheless, this ærolite theory is not very convincing for explaining the lunar features.

The shapes of the ring-formations, with a central cone, recall to the minds of many people the instantaneous photographs which have been taken, with great skill and ingenuity, of a drop falling into a bowl of water. The ring is formed momentarily, and also the central cone. These thoughts have led some people to experiment with splashes—for example, by throwing a ball of clay on the floor—and this does certainly very often give the required shapes.

A snowball, thrown on a cold board covered with a layer of snow, enables every form of crater to be imitated by varying the thickness of snow-layer, the hardness of snowball, etc. This has led to the theory of the moon being a ball of ice, but in the space of this book it would be very unsatisfactory to describe and criticize all these theories, which at present are largely matters of individual opinion rather than of scientific demonstration.

SUMMARY OF CHAPTER III

Every person, without any very serious attention, can find out a good deal about the moon's orbit. Its phases prove that its bright half is illuminated by the sun. Its delay of forty-eight minutes each day gives its period of revolution as about thirty days. The age of the moon from the time of new moon can be reckoned by a simple rule.

A telescopic view shows "craters," "seas," and "white streaks," for the origin of which three theories have been suggested.

The moon is a predominant factor in giving us a view of eclipses (wonderful sights to see, and most informative to astronomers). A total eclipse of the sun is, perhaps, the most impressive of all celestial phenomena.

The movements of the moon in her orbit sometimes appear, at first sight, to be irregular. It is a study of these irregularities, and their full explanation under the guidance of Newton's universal law of gravitation, that has been the strongest confirmation of that law.

CHAPTER IV

THE EARTH, SUN, AND MOON

THE earth, sun, and moon afford the most delightful objects both for man's emotional and intellectual enjoyment.

The earth is a planet filled with the sources of beautiful thoughts, and is the only orb of the universe which we can at all thoroughly examine. The sun is the nearest and the most thoroughly examined of the fixed stars. The moon is the nearest and the most thoroughly examined of the satellites. The examination by us of the three orbs always gives rise to beautiful thoughts. They are also a test of man's intellectual powers in seeking to prove or disprove the absolute truth of the simplest and most comprehensive of all the laws of Nature. For the mutual interaction of earth, sun, and moon raises problems, easy to test by observation, which, while exposing certain limitations in man's existing logical processes, have led him to the extended development of his mathematical powers.

Let us, in conclusion, take note how completely earth, sun, and moon demonstrate the great law of gravitation.

The position of the ecliptic among the stars, the sun's path along it, and the adjacent paths of the known planets, were all observed as accurately as circumstances permitted by the ancients. They all wanted to find some rule for foretelling the planetary positions. They imagined a model of the solar system and assigned orbits in space to those wanderers, the planets. Thus they tried to find a rule for planetary motions, a geometrical rule of position.

They all saw that the sun's movements were part of the rule they were seeking, even that the rule for planets would be found to have a close relation to the sun's position. But not one of them, not even Copernicus, placed the sun on the plane of each planet's orbit, still less on the axis of the orbits they were giving to the planets.

In fact, all that they sought was no more than an empirical rule for predicting planetary positions. They never once dreamed of the sun as being in any sense a cause or the controller of the planetary motions.

This great honour was reserved for Kepler, at the beginning of the seventeenth century, to prove without doubt that the sun possesses some kind of attractive power over the planets, and that the sun occupies the most salient and important position with respect to the orbit of each planet.

Kepler changed the character of the quest, from a purely empirical and geometrical, to an essentially dynamical problem of cause and effect.

The laws of force were at that date completely misunderstood. Galileo laid the foundations of truer conceptions about mass, inertia, and force. In the year of his death (1642) there was born that overwhelming genius, Sir Isaac Newton. He possessed a wonderful power of grasping essential facts and of instinctively choosing the right course, out of several alternatives, for reaching the true theory, and he had a marvellous mathematical power of expressing his reasoning, and an unexampled rapidity with which to arrive at his conclusions. Among many other things, he was thus enabled to give us a dynamical rule of the utmost simplicity, by the correct application of which to all members of the solar system their future movements can be accurately predicted.

Newton held as a first principle of theorizing in natural philosophy that *simplicity* is the keynote to all natural philosophy. When he gave us his great rule, the law of universal gravitation, he proved this contention about simplicity. The whole rule for predicting the future positions of all members of the solar system which have been accurately observed in the past, can be expressed in three lines of print, which contain the whole of the instructions required by a competent computer to enable him to make any such prediction, when he has the past data given him.

From Kepler's first two laws properly interpreted it appeared that a planet or any other piece of matter in space is always being pushed towards the sun's centre. A velocity always in that direction is constantly being given to the planet. If it be at the distance from the sun called the earth's mean distance, or the *astronomical unit*, then, whatever its size may be, the velocity towards the sun which it acquires in the course of a day amounts to 560 yards a second. If the distance from the sun be any number of these astronomical units, the velocity becomes 560 yards a second, divided by the square of that number.

This mode of expressing the facts is clear so far as it goes, but is deficient in that it has no reference to force and inertia or mass. If the sun's mass were increased, the velocity, 140 yards per second, would be increased in the same proportion. Newton went much further, and expressed himself in the language and the conceptions of true dynamics. He thus arrived eventually at the simple law of gravitation, whereby *every particle* (in the solar system, at least) *attracts every other particle with a force varying directly as the product of their masses, and inversely as the square of their distance apart.*

Newton saw immediately that the pure elliptic form of Kepler's planetary orbits must be disturbed by the attractions of other planets. Also that the moon's elliptic orbit round the earth must be very powerfully disturbed by the large solar force constantly pushing the earth and moon towards the sun with various degrees of speed, according to their different distances from the sun.

In fact, *the calculation of these perturbations by the sun of the moon in her elliptic orbit became the principal test of the truth of Newton's theory of gravitation.*

Newton went still further than merely to explain, by his theory, the known irregularities of the moon's motion. He actually foretold other irregularities, disclosed by his theory, which had never been suspected.

And these predictions were confirmed by observations.

Newton's law of gravitation appears to be the one and only fact in the working of our universe which is true for every particle of matter that exists.

Newton's discovery, published in 1687, was not universally accepted on the Continent. From that time till now some of the greatest mathematicians, in concert with the finest observers, have been testing the accuracy of this great universal law. The severest tests have nearly always been connected with the mutual actions of the earth, sun, and moon.

Kepler's laws apply strictly only to the case of two bodies revolving round each other—a planet like the earth revolving round the sun, or a satellite like the moon revolving round the earth.

The earth, sun, and moon opened up the *problem of three bodies*. It has never been completely solved, but only by approximation. The sun's powerful disturbing action upon the steady revolution of the moon round the earth has always afforded the finest test, to make the predictions of theory agree with the observed facts.

The first tables predicting the place of the moon, with sufficient accuracy to enable sailors to find the longitude of a ship at sea, were produced by Mayer in 1770, and were accurate to one and a quarter minutes of arc. We have gone a long way forward since then.

A great astronomer recently made the following statement: "Perhaps the most important astronomical event of the year 1920 was the publication of Dr.

Brown's *Tables of the Motion of the Moon.*[*] It will be generally conceded that all that gravitational astronomy can perform has been brought to its perfection by Dr. Brown."

The only remaining disturber of the moon's motion not included in Brown's tables is due to tides heaped up on the earth, which lag behind the direction of the moon, and, by their gravitative attraction, tend to retard to a minute extent the moon's motion.

The great triumph for the law of gravitation—a complete agreement between theory and observation—was not attained without serious misgivings from the very beginning, owing largely to mistakes in calculation.

1. It is remarkable that the first of these mathematical mistakes was made by Newton himself. The longer axis of the moon's oval orbit is observed to revolve slowly in the plane of the orbit at the rate of three degrees a month. Newton found the amount of this disturbance by the sun's attraction to be only about one and a half degrees. Three of the first geometers in Europe then made the calculation independently. All of them got the same result as Newton did—about one-half of the observed amount.

People began to doubt the accuracy of Newton's law. Finally, Clairaut, in 1749, long after Newton's death, found that, by taking account of some very small effects, considered by Newton and the others to be negligible, the value thus calculated was actually doubled, leading to a perfect agreement between Newton's law and the observed fact. "And thus a circumstance, which at one time threatened to subvert the whole structure of the Newtonian theory, resulted in becoming one of its strongest confirmations" (Grant, in his *History of Physical Astronomy*).

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[*] It is a stupendous production, the result of nearly thirty years of solid work.

2. Other doubts arose from Halley's discovery that the moon's period of revolution round the earth is diminishing. This acceleration of the moon's mean motion was proved by a comparison between ancient and modern determinations. It amounts to ten seconds of arc in a century.

The Paris Academy in 1770 offered their prize for an investigation to see if this could be explained by the theory of gravitation. Euler won the prize, although he arrived at the following conclusion: "It appears to be established by indisputable evidence that the secular inequality of the moon's mean motion *cannot* be produced by the forces of gravitation."

The same subject was twice again proposed for the prize. Both Euler and Lagrange failed to explain it by gravitation.

Laplace then took the matter in hand. In the end he found the acceleration of motion was indirectly due to a change which theory showed to have been going on for thousands of years in the eccentricity of the earth's orbit. Thus was the Newtonian theory again saved, and established more firmly.

3. Exactly the same kind of doubts arose about the truth of Newton's law when an inequality was dis-

covered in the motions of Jupiter and Saturn. Euler and Lagrange failed to explain it by gravitation. Again it was Laplace who solved the problem. He justly said: "These inequalities appeared formerly to be inexplicable by the law of gravitation; they now form one of its most striking proofs."

There still remain three small discrepancies which have not yet been brought within the theory.

1. The researches of Dr. Brown and others prove the existence, after all known effects have been dealt with, of a fluctuating error in the moon's place having a period of 250 years.

2. Encke's comet, whose returns have been observed every three or four years for more than a century, has shown a decided diminution in its period of revolution not yet accounted for by Newton's theory.

3. The exact rate of motion for the longer axis of Mercury's oval orbit, as determined by the gravitation theory, does not come out quite in agreement with observation. It is the same kind of error as Newton and the other mathematicians failed to correct in the moon's motion.

Any one of these may be taken up as an argument against Newton's law. There is little doubt that, as before, Newton's law will triumph in the end. As a matter of fact, the last-mentioned minute disagreement between the theory of Mercury and observation (concerning the true value of which there is much doubt) is the only point in gravitational astronomy that has led Einstein to invite astronomers to discard part of the teaching of Sir Isaac Newton. He has made no attempt to deal with the discrepancies marked 1 and 2. The fact is that his theory is not based upon astronomy, but on physics and metaphysics. Perhaps he will explain later by his theory the puzzling behaviour of the moon and Encke's comet. This would be a real triumph. On the other hand, it is possible that simpler explanations, apart from his theory, may again solve such problems, as they have so often done in the past.

This is not an occasion for applauding the prodigious intellectual achievement of Einstein, acknowledged by all. And certainly this is not an occasion for throwing any doubt whatever upon the convincing arguments by which he has captured so many adherents to his splendid speculations.

There is every reason to hope that Newton's simple law will be found to explain these three irregularities, and again to receive confirmation from supposed defects.

"O ye Sun and Moon, bless ye the Lord: praise Him,
    and magnify Him for ever.
  O let the Earth bless the Lord: yea, let it praise
    Him, and magnify Him for ever."

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THE STARS

By GEORGE FORBES
M.A. (Cantab.), Hon.LL.D. (St. Andrews),
F.R.S.

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THE STARS

CHAPTER I

ORION, THE MAGNIFICENT

THE beauty of a starlight evening appeals to every person at one time or another, whatever be his walk in life. Yet it is difficult to define what it is that creates this special charm, this appeal to our higher nature.

Millions of men and women share the regret of Thomas Carlyle when he said: "Why did not somebody teach me the constellations, and make me at home in the starry heavens which are always overhead, and which I don't half know to this day?"

The stars are seen by us to differ among themselves in glory. We can detect no uniformity in magnitude, no symmetry in their arrangement; their numbers and distances are incredible; their origin a mystery; and we long to know more about them. There may be some who do not feel, so intensely as do we lovers of the stars, the glory of the picture of Orion in his starry frame; just as there are some whose hearts do not respond to the charms of music or the beauty of a garden. This book is written for those who do instinctively love the stars, and who want to know them more intimately, to call them by their names, to recognize them, and to be able to tell a friend something special about each different star, and the wonderful discoveries that have been made in regard to Sirius or Mizar or Spica or Algol or any other old friend among the orbs of heaven.

* * * * *

The ancients used to picture some well-known figure (often an animal or a mythological hero) to cover a group of stars and to name them as members of that constellation. The superb constellation—Orion, the hunter of mythology—as seen from northern latitudes in the southern part of the sky at midnight in December, can be identified by the following description: Mark upon paper five dots like a St. Andrew's cross, or like the five of diamonds. On this draw a man's figure facing you, with the two top dots for his shoulders, and the two bottom dots for his legs. The middle dot is his waist and belt, and we mark it by three dots in a nearly horizontal line, where three notable stars lie. Add to this a head which, in the heavens, is shown by a few small stars. If, in addition, you hang from the belt a sword scabbard pointing downwards, you have a fairly complete picture of the stars we see in the constellation Orion.

Afterwards, you will be repaid if you take the sketch outside to compare with the actual stars and to make corrections as well as additions. The first correction might be to make the three prominent stars in Orion's belt incline a little downwards to the left, pointing eastward to the brightest star in the whole sky, and the nearest of all stars visible to the naked eye in British latitudes. This is Sirius, the Dogstar. These three stars of the belt are the most notable feature by which we can always recognize Orion. The fact that these equally bright stars, equally spaced

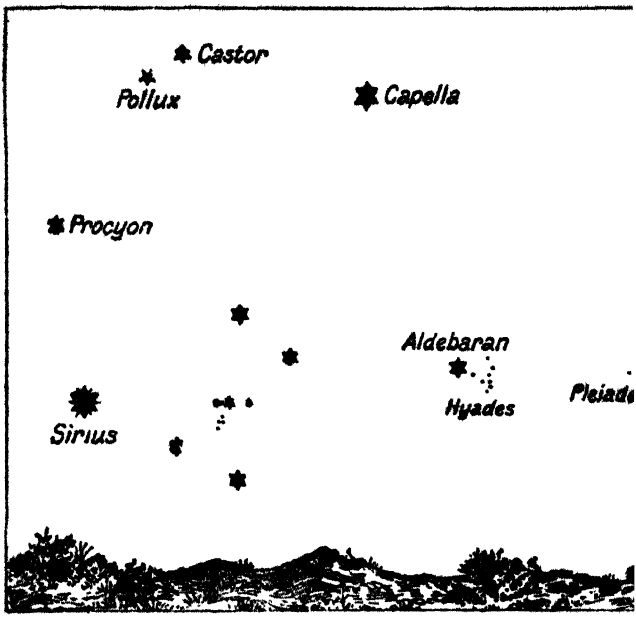

FIG. 1.

The most pleasing orientation for viewing the most glorious picture of stars in any part of the heavens. Orion in centre surrounded by Sirius, Procyon, Pollux and Castor, Capella, Aldebaran, with Hyades and Pleiades to the right; as at 9 p.m. in March.

in a straight line, point directly to the great star Sirius confirms us in our recognition of Orion. The peasants in Provence call them "les trois rois," the three kings, who had seen the "star in the east," represented here by Sirius, the lord of all the stars.

Astronomers have drawn a definite boundary line on their star-charts to enclose this picture of Orion as his kingdom. So they have done with all the constellations. In this way the whole heavens have been portioned out into constellations, as our continents are portioned out into countries.

To most persons Orion is known as the grandest of all constellations, partly for its own sake, partly as a rallying point during our visits to all the other stars and constellations, and largely because of the extraordinary brilliance of the starry jewels, which frame it, as it were, in a triumphal arch of stars—Sirius, Procyon, Pollux, Castor, Capella, and Aldebaran. The three stars of Orion's belt point to the two great stars at the base of that arch, to Sirius on the left, and, less exactly, to Aldebaran on the right. And, passing across over Orion's right shoulder as he faces us, is the band of faint white light, which goes by the name of the "Milky Way."

* * * * *

In many ways our antipodean friends have even more magnificent starry pictures than we who live in northern climes. Thus it happens that in New Zealand you can, on looking northwards at midnight in December, see not only Orion, upside down, it is true, with every member of the triumphal arch of stars that have been named, all of these above the horizon; but also, at the same hour, other brilliant stars of first magnitude never seen in Britain, named Canopus, Achernar, Alpha, and Beta of the Centaur, and the stars of the famous Southern Cross.

A further advantage is possessed by our cousins of the southern hemisphere. In our northern position the part of the Milky Way which we see looks like a broad, faint streak of whitewash over the left upper part of Orion, continued straight on in both directions, beginning and ending at the horizon, always rather faint. Our friends in the southern Dominions, in India, and in many of our Colonies, when looking at the Milky Way, are witness of certain gloriously bright clouds of shining milky star dust of which the southern half of the galaxy is largely built up, an arresting feature there on any moonless night. They also can behold the "rift" in the midst of its radiance, and the black starless "coal-sack." They also have a sight, denied to us, of the greater and the lesser "Magellanic clouds" as they are called, which look like clouds or wisps of the Milky Way detached from their parent, floating alone, clear and distinct to the naked eye.

Even among the brightest stars the New Zealander has advantages over us at home. For he is able to see every one of the twenty-one brightest stars in the sky, though Capella and Deneb, two of our northern stars, are only just above his horizon. Of course, anyone living exactly on the equator, with a clear horizon to the north and south, can, at one time or another, see every star in the whole heavens.

* * * * *

Returning now to our northern picture of Orion surrounded by its arch of triumphal stars, we may take note that people have given to each bright star in the sky a familiar and a friendly name of its own like *Vega*. But it is also known by the family name of its constellation; with a Greek letter alpha, beta, gamma, delta, etc., or a numeral, for the initial of its Christian name. Let us, then, identify Betelgeuse, on Orion's right shoulder as he faces us, as being otherwise called Alpha of Orion, and the very bright Rigel on his left leg, called also Beta of Orion. In the arch of brilliant stars round Orion we identify, at its left base Sirius, to which Orion's belt points, as Alpha of the "Greater Dog." Above Sirius no one can fail to notice another lone white star. This is Procyon, or Alpha of the "Lesser Dog." Then, following the left side of the arch upwards, you will see a bright pair of golden stars still higher in the sky, Pollux first, then Castor, Beta, and Alpha of the "Twins." And nearly overhead, at midnight in December, is the splendid Capella, Alpha of the "Charioteer." Lastly, at the right base of the arch of stars, is a somewhat ruddy star, Aldebaran, or Alpha of the "Bull." (See Fig. 1, p. 5.)

Already, in a single night, anyone can make the acquaintance, never to be forgotten, of all the stars in Orion, of Sirius in Canis Major, Procyon in Canis

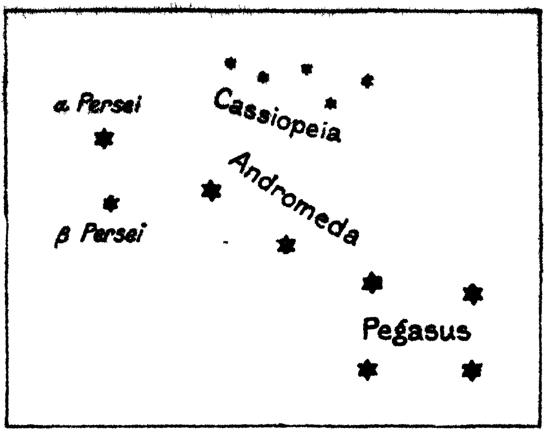

FIG. 2.

The Square of Pegasus, Andromeda, and α Persei. β Persei is Algol, the wonderful variable star. Due south at midnight in September.

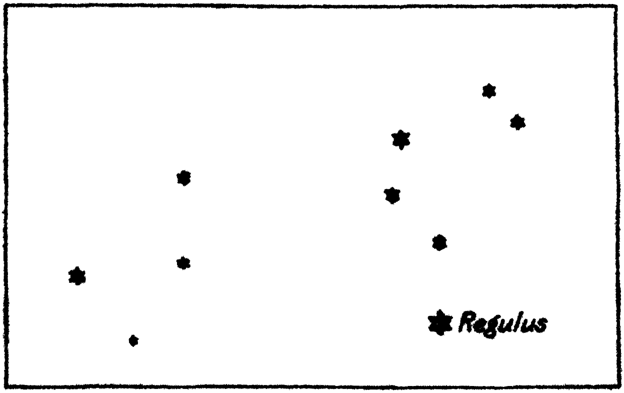

FIG. 3.

The Lion, whose head resembles a reaper's sickle. Due south at midnight in February.

Minor, Castor and Pollux in Gemini, Capella in Auriga, and Aldebaran in Taurus. (The Latin names of constellations are commonly used.)

These six stars form a more complete and symmetrical arch some hours after midnight at Christmastide or, for example, at 9 p.m. in March, as seen in Fig. 1.

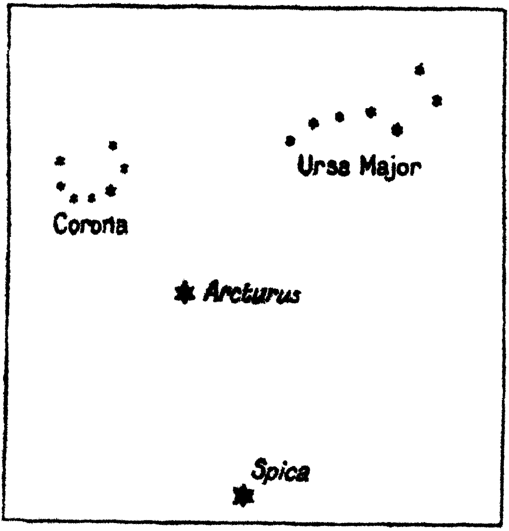

FIG. 4.

The curve of the Bear's Tail if prolonged passes through Arcturus and Spica. Due south at midnight in April.

It will be found convenient to use Orion as a starting point from which to fix in our minds the order in which other constellations lie. We have to remember that it lies due south of us at midnight in December; or at 10 p.m. in January; or 8 p.m. in February; always two hours earlier for each later month, because a circuit of the heavens is made in twenty-four hours, or in twelve months. And it rises, or sets, about six hours earlier or later than the hours named here.

Orion is *preceded* in its rising, and its nocturnal march across the sky, by the Bull with its ruddy bright star *Aldebaran*. It, in its turn, is preceded some four hours earlier by a great square of four stars of the constellation *Pegasus* (Fig. 2).

Orion is *followed* by the *Twins*, by *Sirius*, and *Procyon*, and later by the *Lion* (Fig. 3). The six stars forming the lion's head outline a reaping sickle, with the bright *Regulus* at its handle. And the *Lion* is followed in four hours by the bright star *Spica* near the southern horizon. This is Alpha of the *Virgin*. Above it lies Arcturus, or Alpha of the herdsman, Boötes (Fig. 4). The tail of the Great Bear guides our eye to these.

CHAPTER II

STARS THAT NEVER SET

STARS ROUND THE NORTH POLE

WHILE the picture of Orion is still before us we may do a little practical astronomy. Choose a high wall with its sides pointing north and south. Stand at its north end and, looking southwards along the left, or eastern, side of the wall, you can now, at midnight in December, see that it seems to cut the sky just where Orion is. Perhaps one of the stars in Orion's belt is just appearing to the left of the wall. Watch that star for a quarter of an hour and you will see it disappear behind the wall. In other words, the Orion stars are travelling westward. Of course we all know that really it is the earth that rotates in the opposite way, carrying us with it.

Now go to the south end of the wall and you will see that the stars high up in the sky, like our friend Capella, overhead, travel much more slowly to the west (now at our left), while those low down near the north horizon actually travel in the opposite direction, to the right, which is eastward; and at a certain point pretty high up the motion of the stars is insensible. This marks the pole of the heavens.

If at any hour of the night you hold a straight rod over your head to pass from Orion to Capella, and carry your eye as much further along the same line, you will then reach a moderately bright star in the north. You have, in fact, discovered the Pole Star, round which the whole vault of heaven, carrying all the fixed stars and planets, and sun and moon, seems to revolve once in about 24 hours, Really it is our earth that completes a rotation in 23 hours 56 minutes by our clocks. This is the interval of time taken by every fixed star, which we have seen to be in line with the north and south wall, before it returns again to hold the same position; four minutes short of a solar day.

Anyone who possesses a camera with rapid lens (short focus, large aperture) would be delighted to see the result of exposing a rapid plate in the direction of the Pole Star. Fix the camera in position and leave it to expose for two hours. The result may be almost unseen in the negative, but a print will show the rotation of the stars round Polaris, the Pole Star. This star is almost motionless; each of the other stars describes a twelfth of a complete circle in the two hours, so the streak shown by each star has a greater length the farther that star is from the Pole Star. The resulting picture is very convincing as to the earth's rotation.

The apparent daily and nightly motion of the whole heavens is really caused by the motion of the earth on which we stand. It rotates on its axis once in 23 hours 56 minutes of solar time, or 24 hours by a clock regulated to go quicker, for the stars, to give "*sidereal* time." When we have such a sidereal clock, each star is found to cross our line of sight, along the surface of the north and south wall, always at the same hour of sidereal time, on every night of the year during which that star can be seen at night. In fact, we can thus identify every individual star by the hour (sidereal) when it crosses our wall, and its height above the horizon.

* * * * *

How to find the Pole Star at any time of Night.—You have already discovered certain facts about the rotation of the earth, as shown in the daily motion of the stars. One fact is clear, that stars seen just above the north horizon never set, and many stars, being nearer to the Pole Star than is our northern horizon, can never set. There are also stars in a circular region round the South Pole which we never see.

There are two very notable constellations near the North Pole at nearly equal distances from the Pole Star, in opposite directions from it. One is called the "Great Bear," out of which seven bright stars go by the name of the "Plough" in England, and the "Dipper" in the United States. The other constellation is called "Cassiopeia," or "Cassiopeia's Chair."

These circum-polar stars, being always above the horizon, are *always* available as a guide, so long as we have no clouds, for finding firstly the Pole Star, and then all the other stars. The seven stars of the Plough are so easily recognized, whether seen direct below the pole or upside down above it, or sideways, that it becomes a splendid guide. Four of its stars form the ploughshare in front, the other three are the handle of the plough behind, and the plough's forward course shows the direction of its nightly revolution, towards the star Capella, already an old friend.

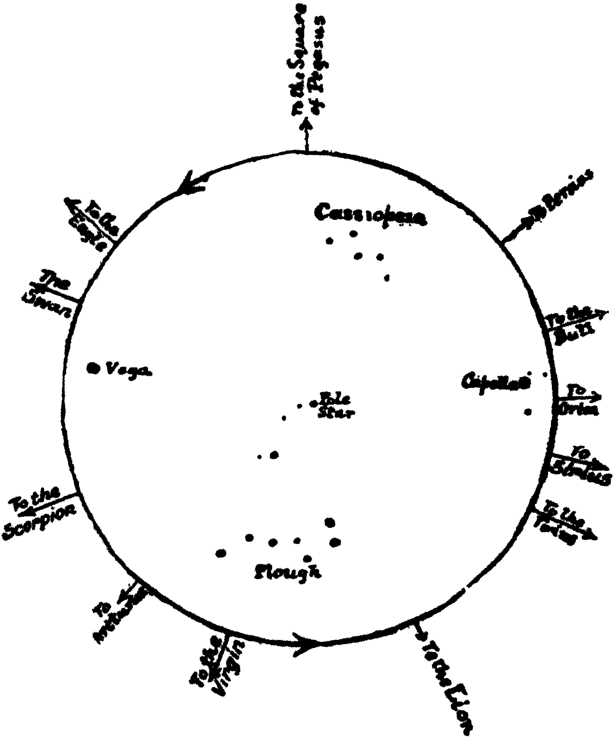

FIG. 5.

Key-map of Circum-polar Stars, rotating nightly round the Pole in the direction shown by arrows.

The two front stars of the ploughshare are called "the pointers." They point to the Pole Star, about as far from them as the length of the plough.

Next, continue a line from the middle of the Plough, through the Pole Star, and as far beyond. You then reach the constellation Cassiopeia, or Cassiopeia's Chair, consisting of five stars lying in the shape of a W.

The other quarters of a ring drawn round the Pole Star as centre are occupied by Capella in front of the Plough, and Vega, a lovely bluish star, behind the Plough. Vega is accompanied by two small stars forming with itself a regular triangle, very small, but useful for assuring us that this is really Vega, or Alpha of the "Lyre" (see Fig. 5).

* * * * *

Having now discovered and mapped out the circular chart of northern circum-polar stars, we have a guide to all the constellations, and a key to the special stars which appear at any hour of any night in the year.

My own special Boy Scouts used to mark the inside of an umbrella with white bits of paper for the stars in the Plough and Cassiopeia, for Vega and Capella. They would point the top of the umbrella to the Pole Star, and turn it round till Capella was overhead. This gives the position of all of these stars for midnight in December. A quarter of a turn to the left gives the position 6 hours, or 3 months, later, and this brings the Plough, upside down, to the top, and so we learn that this is the position for 6 a.m. in December, or for midnight in March. Vega is at the top in June at midnight; and Cassiopeia in September. A quarter twist forward or backward represents either the 3 months at a fixed hour or 6 hours at a fixed date. Thus the Boy Scouts were able to give for any hour at any time of the year the correct position of the umbrella to represent truly the positions of the circum-polar stars. They could even tell the time of night, roughly, from the star positions, by their handling of the umbrella.

But they went a step further. They hung a curtain round the rim of the umbrella, and marked the most prominent stars on it by little bits of paper. For example, we already know that Orion would lie upon this curtain, under Capella.

Finally each of them kept a card with a circle containing the circum-polar stars, and arrows to mark the positions of stars and constellations with which they were familiar. This card, as shown in Fig. 5 (p. 15) became a guide to the heavens, as well as a kind of astronomical clock; and some boys did not need the card. They came to know it by heart, and could work out the star positions for any date and any hour in their heads.

* * * * *

A circular chart of the same character can be made for the southern circum-polar stars. Here the guiding constellation is the Southern Cross, a fine group when upright, although we miss a middle star as demanded by the form of a cross. When voyaging towards the Cape, on reaching the trade-wind latitudes near the Cape Verde Islands, some 20° north of the equator, at midnight in March, or at any other month and hour when the Plough attains its highest point in the north, the traveller sees the Southern Cross standing upright over the southern sea horizon, pointing downwards to the south pole of the heavens, which is 30° below it. Thus did Sir David Gill first see it when on his way to the Isle of Ascension in 1877, in hopes of solving the vexed question of the true distance of the sun. And he has told me how impressed he was at this aspect of the Southern Cross shining in the bright Milky Way close to its black, starless, pear-shaped emptiness called the "coal-sack"; and how he took the upright Cross as an emblem and omen of success to his hopes. And, to the joy of all astronomers, success followed the omen.

To the left, and pointing to the Cross, are two first magnitude stars, Alpha and Beta of the Centaur. These are brilliant guides to the Cross, which itself is always above the horizon in high southern latitudes, and is used very generally by huntsmen and travellers, not only to replace the compass by showing the south point, but also for telling the time by the slope of the cross to the horizon.

The brightest of southern circum-polar stars is Canopus, the greatest of all stars in the heavens except Sirius. These two stars, Sirius and Canopus, are seen to rise and set nearly at the same hour, if we are on the equator.

That half of the southern circum-polar region wherein the Cross lies centrally exhibits a brilliant part of the Milky Way, dotted with many bright stars. The other half that is on the opposite side of the South Pole is singularly devoid of these. Achernar alone, called also Alpha of Eridanus, of the first magnitude, shines brightly in that part of the heavens.

Everyone wants to know the names, at least, of the bright stars, and of the striking groups of stars called constellations. The brightest *fixed stars* are, in order of brightness: (1) Sirius, (2) Canopus, (3) Alpha of the Centaur, all in the southern half of the sky. Then come (4) Vega, (5) Capella, (6) Arcturus, in the northern half. After these we have, in order of brightness, (7) Rigel in Orion, (8) Procyon, (9) Achernar, (10) Beta of the Centaur, (11) Altair in the Eagle, (12) Betelgeuse in Orion, (13) Alpha of the Cross, (14) Aldebaran, (15) Pollux, (16) Spica, (17) Antares, (18) Fomalhaut, (19) Alpha of the Swan, and (20) Regulus.

All of these are often spoken of as first magnitude stars; although the first one, Sirius, is sixteen times brighter than the last one, Regulus.

CHAPTER III

THE WANDERING STARS

The Planets

It often happens that the star which catches our eye is not a fixed star, but is one of the wandering stars, or planets, concerning the appearance of which a few words must now be said. Jupiter, Mars, Venus, and the other planets differ from the fixed stars principally in two respects. They are not fixed, but move about from one constellation of stars to another, along a straight, continuous path, nearly the same for all of them. And again, each of them varies in brightness from month to month, and it is only now and then that any one of them actually compels our attention by its brightness.

It may surprise some of the less careful watchers to know that there are only five of these planets ever visible to the naked eye. All of them are occasionally very bright. They are Mercury, Venus, Mars, Jupiter, and Saturn. And for practical purposes Mercury may be left out of account, because he is small, and, being never more than thirty-three degrees away from the sun is not so often seen in our climate.

The four principal planets, brilliant lamps of the sky, are admired by all, and often we hear the query: "What is that lovely star we see every evening now in the west?" The answer is very sure to be: "The planet Venus"—a round planet shining, like all the planets, by reflecting the sun's light, and showing in a telescope all the phases of the moon, but in a year and a half instead of one month. It is nearer to the sun than our planet the earth.

Sometimes the query may take this form: "Before going to bed, lately, we have been noticing a wonderful great star in the south. What star is it?" The answer will be: "It must be one of the three planets that are further from the sun than our planet the earth—either Mars, Jupiter, or Saturn." An astronomer might, of course, know which of them is in that direction at that time. But a moment's inspection would suffice to make this known to anyone who cares enough about the stars to notice things for himself.

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HOW TO KNOW THE PLANETS.—There are three ways of knowing a planet as such when we see it. The first two are very quick and easy to apply, but not so certain as the third. The first clue is this: Whenever you see an unusually bright star, unless it be Sirius, it is probably a planet in that part of its orbit where it becomes brightest to the inhabitants of our planet the earth. Take Venus, for instance, on a circle that is always inside the earth's orbit. She does not shine by her own light. The half of her next the sun is lighted by the sun; the rest of her is dark to us. So, when Venus is nearest to us, we are looking at her dark side, which is invisible. When she moves a little away from that position we see a little of the illuminated half like a crescent moon. Venus is never at a greater distance from the sun than about forty-five degrees. When at that place she looks in the telescope like a half-moon. She is then nearly at her brightest. For when she goes farther round, turning to us the whole of the illuminated hemisphere, she is so far away that the light is much feebler.

During the period that Venus is about forty-five degrees from the sun she is brighter for weeks than any other star or planet, and can easily be seen before sunset. In fact, she can then be seen sometimes at midday, if you know where to look; and I have seen her casting a shadow on the deck of a steamer.

None of the other three planets is at its brightest when near the rising or setting sun. For they are then near their greatest distance from us. So, if we see an extremely bright star in the west at sunset, or in the east at sunrise, we are very safe in asserting that it is Venus.

As to the other planets (Mars, Jupiter, Saturn) outside the earth's orbit, they are brightest when nearest to us—that is, when sun, earth, and planet are nearly in line, and in that order, and we see the whole hemisphere of the planet that is illuminated by the sun from the dark side of the earth. That is why a very bright star in the southern sky, long after the sun has set, is probably Mars, Jupiter, or Saturn.

It is generally possible to judge, by mere inspection, which of the three planets we are looking at.

Mars is always red, and becomes fiery red when it is nearest to the earth and at its brightest. Jupiter is much the largest of all the planets, and is invariably a very bright star; but he has not the red colour of Mars, which colour is doubtless due to the sandy soil of Mars. The more distant planet, Saturn, is duller and yellowish.

With a pair of opera glasses Jupiter can always be positively recognized, because he has four moons large enough to be almost visible to the naked eye, besides five very small ones. Some of the four Galilean moons (discovered by Galileo)—often all four—may be seen at any time with a small glass, and, as they are close to Jupiter and all lie on a line going through the planet, they cannot be mistaken, though constantly changing position. If, then, the glass shows three or four small specks of light on a line going through the planet, we may be sure we are looking at Jupiter. These moons changing their positions on the line are a constant delight to anybody with a small telescope.

If you direct upon the planet Saturn a telescope larger than the little one that suffices to show Jupiter's moons, you know at a glance which planet it is. For it is not round, but elongated, owing to the marvellous flat ring that surrounds its equator, generally tilted at an angle.

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The second clue for identifying a planet among the stars is most useful when the planet is not at its brightest—not brighter than some of the fixed stars. *The fixed stars generally twinkle, the planets almost never.* Everyone has noticed on a clear night the rapidly changing brightness of stars, called twinkling or scintillation, often accompanied by sparkling colours like the flash from a diamond. It is caused by small patches of irregular density in the atmosphere which deflect from the eye a ray of light that ought to reach it. The effect is momentary, because the patches are in motion and quite small. It is constantly repeated, because there are many patches. Some stars twinkle more than others.

Everyone knows that our atmosphere bends a ray of light from a star downwards, and that the light of a star contains rays of different colours that are bent to different degrees by the atmosphere. Thus the rays of different colours of which a star's light is composed do not all follow exactly the same paths from a star to our eye. It follows that the atmospheric patches causing scintillation, in their motion, deflect the different colours, not all at once but in succession. If green be deflected from the eye the star looks red, and *vice versa*. This is easily seen in a spectroscope attached to a telescope. But a very pretty experiment may be made without any special apparatus, showing the effect in a beautiful manner.

If a small telescope or an opera glass be pointed to a star, and if we keep on tapping the instrument, then the star seems to move about. Its image persists on the retina for a fraction of a second. So the moving star-image looks like a string of light that can be twisted into a coil of different shapes by judicious tapping.

Now, if the star be a good twinkler, the string of light seems to have gaps in it, showing when a patch is deflecting the ray of light out of our line of vision. But this is not all. The patch deflects different colours in succession. Sometimes green, sometimes red, is deflected from the eye. The result is that the string or coil of light is converted into a beautiful pearl necklace, interrupted, not by mere dark gaps, but by the brilliant scintillations from diamonds, rubies, sapphires, and emeralds. Try this experiment, and show it to your friends.

These remarks on twinkling help to explain why fixed stars twinkle and planets do not. A star is at such an enormous distance that, in spite of its great size, it looks like a mere point of light. But a planet is near enough to show a disc of sensible size in a telescope. A patch in the atmosphere may deflect from our line of sight a ray of light coming from a point like a star, and yet be too small to affect all the rays coming from different parts of the planet's surface. This is the reason why you may be sure that a star which twinkles is not a planet.

The two clues already given for distinguishing planets from other stars are not absolute. The third clue is the only sure and certain test. It depends upon the position of the doubtful object among the other stars. After we have got to know some of the constellations, and noted the places occupied by planets, we make this great discovery: that planets do not turn up in all parts of the heavens. In the greater number of the constellations planets are never seen. There is, in fact, only one straight road or track among the stars, and not a very broad one, in which we ever see a planet, or the moon or the sun. At first it seems almost absurd to speak of the sun following a track among the stars, as we do not see the stars in daytime. But this happens only because the sun's light illuminates the atmosphere and makes it brighter than the stars. It is a surprising truth that the stars are shining just as brightly by day as by night. The sun and the moon, being both wanderers among the stars, were in old days included among the planets.

How can we trace the path among the stars which is followed by the sun, the moon, and the planets? Sometimes we have the good fortune to see three planets at the same time. In that case we can see for ourselves that the path is a straight line right round the earth. It is not easy to imagine correctly a straight line among the stars. The best plan is to hold up a walking-stick, and we find that it covers all three planets at the same time, provided no two are very close together. This is true all through the year, so the track is continuous right round the earth. Thus we learn from our own observation that the planetary orbits all lie nearly in one plane through the sun.

While holding the stick in line with any two planets it is easy to note those stars and constellations that are covered by the stick, and to continue the line among the stars that form the apparent path of the sun, the moon, and the planets. This path is called the ecliptic: a word strictly used for the path of the sun among the stars, but applicable also as a nearly perfect guide to the paths of the planets and the moon.

In this way we might be fortunate enough to see the moon halfway between Aldebaran and the Pleiades, while Mars might be in the Twins, a little farther from the Pole Star than the bright stars Castor and Pollux. If Saturn happened at the same time to be near the bright star Regulus in the Lion, and Jupiter at Spica in the Virgin, we should be able very easily to trace out with our stick the whole of the northern half of the ecliptic, which, to us, in these latitudes, is its most interesting part. The only other really bright star on the ecliptic is Antares, in the Scorpion, more favourably situated for people in Southern latitudes.

With the help of a star atlas, or some *Easy Guide* containing pictures of the constellations, it is a very simple affair to get to know the constellations lying upon the ecliptic, the twelve signs of the zodiac, which divide the yearly path of the sun into twelve months. This occupation goes far towards completing our familiarity with any stars that happen to be shining, at any time of the year.

After this has been done no one can be in doubt about a planet. If a star we are looking at is not on the ecliptic it cannot be a planet, and, knowing all the bright stars on the ecliptic, we cannot mistake them for planets. The names of these constellations of the ecliptic, called signs of the zodiac, if remembered in their proper order, are a great help towards recognizing other stars.

They are:

Aries *Taurus* *Gemini*
The Ram, the Bull, the Heavenly Twins,
Cancer *Leo*
And next the Crab, and Lion shines
Virgo *Libra*
The Virgin and the Scales,
Scorpio *Sagittarius* *Capricornus*
The Scorpion, Archer, and He-goat,
Aquarius
The Man who bears the Watering-Pot,
Pisces
The Fish with glittering tails

Only some of these constellations are conspicuous. The Bull will be recognized by its bright star Aldebaran and the little cluster of stars called the Pleiades; the Twins by Castor and Pollux; Leo by its sickle-like shape and the bright star Regulus; the Virgin by Spica; and the Scorpion, rather near to our southern horizon, may be recognized in summer by the bright red star Antares.

Using some small star atlas with an electric torch, anyone can see nearly all of these in the course of a single night; the ecliptic constellations following one another in the order given above.

CHAPTER IV

THE ARCHITECTURE OF THE FIRMAMENT

Our imagination is apt to run riot when we begin to speculate about the universe of stars which forms our stellar system, with our solar system somewhere in the middle of it. We want to know more about the number of the stars, their incredible distance from us, and the purpose they serve in those far away regions of space. Do the starry regions extend to infinity? Or has the universe of stars some definite boundary? And if it has, what is the shape of the boundary? As to the different regions of space that are occupied by stars, are they all filled with stars to the same extent? Or are some regions more crowded, others more empty? Can we discover the size, weight, temperature, etc., of different stars? And in these respects are there different kinds of stars in different parts of space, like the human differences on our four continents—white, yellow, red, and black men? Or is there the same kind of star in every region of space? Do they undergo changes in size, brightness, etc., in the course of ages? Whence do the stars derive the energy that maintains them as hot shining things? Are they absolutely fixed in position? If not, do they move singly or in battalions? Does gravitation, universal in the solar system, extend to the stellar distances?

Suchlike questions have always intrigued, and will always intrigue, those astronomers who are blessed with a powerful imagination or insight into the unseen. No astronomer who is loyal to astronomy, the queen of the sciences, our glorious science of absolute truth, ever claims for his pure speculations more than this—that, at best, they can be no more than an expression of the most probable guesses or opinions concerning the limited number of facts that constitute our small amount of knowledge, or great amount of ignorance, at the present time. And such an astronomer never forgets that the present time is a very early century of the world's progress in discovery.

Bearing this in mind, it is permissible to derive the highest possible intellectual enjoyment, not only from the established truths of our science, but also from the ingenuity of pure speculations which have led to some of the most fascinating, all-embracing guesses or hypotheses. These are to-day being supported in the hope that, under test, some of them may have more than an ephemeral place in the history of astronomy. The amount of progress in this direction during the present century has been enough to extend our outlook upon the stars from a mere state of wonder and curiosity almost to a personal friendship, and certainly to an overwhelming interest and joy in the marvels to which each star in its own way does bear witness. It often does this in a language free from any ambiguity, whose dictionary we are still engaged upon compiling, by observation of the stars, and by experiments in the laboratory.

It may seem almost incredible to many that the number of stars we see at any one time never exceeds some two thousand; but this is true. Of course, we have only half of the stars above the horizon at once, and, near the horizon, faint stars are generally dimmed by haze. And further, the middle part of the retina of our eyes is less sensitive to the light from a star than other parts; and it is only the picture of external objects upon the retina that we see, and not the objects themselves. Hence, in a casual glance at the stars, we see a great number indirectly, which disappear when we look straight at them to make sure before counting them.

This is the reason why, without clearly seeing them, we do get a glimpse of many more stars than the two thousand or so that we can count with the naked eye.

In the year 1610, Galileo first pointed his little telescope to the white streak across the sky which we call the Milky Way. He discovered in a moment the surprising truth that its light comes from innumerable minute stars, too feeble to be seen individually without a telescope.

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STAR MAGNITUDES.—The brightest stars, some twenty of them, are spoken of as *first magnitude* stars, though they differ in brightness. The Greeks used the name, and divided the visible stars according to magnitudes. They called the faintest visible stars sixth "magnitude," those of intermediate brightness being magnitudes 2, 3, 4, and 5.

This nomenclature is unfortunate, as the star of greater "magnitude" is the fainter. To give the system greater precision, we now say that each magnitude is 2½ times brighter than the next, or that the brightness is 100 times greater for a difference of 5 magnitudes (noting that 2½ multiplied by itself 5 times is almost exactly 100). Thus we say that a star of magnitude 1 is 100 times brighter than the *faintest* we can see, of magnitude 6.

The smallest star that can be detected with a very large telescope is about magnitude 21, or 20 magnitudes difference from a star of magnitude 1. If 2½ be multiplied by itself 20 times, we get nearly 100,000,000. So a first magnitude star is a hundred million times brighter than the faintest star to be seen in that powerful telescope.

Aldebaran in the Bull is almost exactly of first magnitude. Our old friend Vega is 2½ times brighter, a difference of 1 magnitude, and is very properly described as being of zero magnitude. Sirius, the monarch of fixed stars, is so bright as to have the *negative* magnitude −1·6. The sun's brightness is given by the negative magnitude −26; ten thousand million (10,000,000,000) times brighter than Aldebaran as seen by us.

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THE NUMBER OF STARS.—The number of bright stars is far less than the number of fainter ones. There are only 2 stars brighter than magnitude 0; 11 brighter than first magnitude; 39 for second; 133 for third, 446 for fourth, 1,466 for fifth; and 4,732 for sixth magnitude.

Passing on to those seen with a telescope, the estimated numbers increase to gigantic numbers: 139,300 for the ninth magnitude; 2,588,000 for the twelfth; 27,540,000 for the fifteenth; and the estimated number of stars brighter than the twentieth magnitude is 530,900,000.

With the largest telescope in the world to-day, the 100-inch diameter reflecting telescope at Mount Wilson, U.S.A., there are probably over a thousand million stars that could be detected on a photographic plate.

Astronomers at Greenwich Observatory have estimated, on fairly good grounds, that the total number of stars in space belonging to our stellar system is limited to three or four thousand million. An American estimate is thirty thousand million stars. The investigations on which these estimates are made indicate that beyond some unknown but definite distance there comes a limit beyond which there are no more stars belonging to our star system. And further, that this limiting distance is far greater in directions towards any part of the Milky Way than towards other parts of the heavens.

Astronomers of to-day, however, are inclined to believe that far beyond these limits there are many other isolated star systems like our own. These are the telescopic *cloud-spots* among the stars called " white nebulæ," such as the Great Nebula of Andromeda. And it is suggested that if there be inhabitants of planets in that system, they would see *our* stellar universe in a powerful telescope like one of these cloud-spots as seen by us.

It is a startling conclusion, at this date commonly accepted, that our own universe of stars is strictly limited in extent, and also in the number of stars contained in it; and that it is even possible to get a close estimate of the shape of the boundary within which our star system is enclosed.

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Distribution of the Stars.—Is there any concentration of stars in the different directions of the heavens? Let us consider the bright and faint stars separately. The nearer a star is to us, the brighter it will shine. The stars we see without a telescope are the brightest stars and, on the whole, probably the nearest. None of us, however, would say that we notice any overwhelming concentration of these in any parts of the sky. On the other hand, we do know that the Milky Way owes its appearance to myriads of faint telescopic stars, which must, on the whole, be more distant because they are so faint. Thus, while the near-by stars seem to be uniformly distributed in all directions, there is an intense concentration for the more distant stars, along that bright belt which is seen in the heavens to encircle our position in space.

Thus we are led to the truth that the boundary of our stellar universe extends to greater distances wherever the Milky Way lies than in all the other directions. And it has now become clear that most of the stars exist there, in a very extended flat ring of comparatively small thickness, surrounding us, going to enormous distances, while in other directions the region occupied by stars is much more restricted as to distance, and exhibits hardly any very faint stars.

In fact, it has been truly said that, if you could blot out all the stars seen in a 12-inch telescope, the fainter stars which could be seen with a larger telescope would be found to lie almost entirely in the Milky Way. Already we begin to foresee what is true—that this streak of faint light in the sky, to which we used to give but little attention, will prove to be a principal factor in the architecture of the heavens.

Although not brilliant in its northern parts, the Milky Way in its southern half contains the brightest and the most arresting patches of the starlit clouds of glory, with the contrasts of jet-black rifts and blank spots, separating, for example, the bright cloud of Sagittarius the Archer from that of Ophiuchus, or like the " coal-sack " of the Southern Cross in the middle of a brilliant patch. We can well be lost in admiration at the sight. The wonders of these starlit clouds of glory are best exhibited by the photographs which were made by Barnard at the Lick Observatory in California. They came as a revelation to the present writer at the time. It was during a memorable night spent with the great 36-inch refractor there in 1894. Barnard had then begun to take these photographs with an ordinary portrait lens, the camera being strapped to an equatorial telescope, for following the stars by clockwork, while Barnard himself, during hours of close attention with the telescope, was able to correct any irregularities of the motion. He produced numbers of the most detailed and beautiful photographs in different parts of the Milky Way, solely by his laborious patience in observation.

Distances of the Stars.—Immense as is the number of the stars, their distances from us are still more appalling. The human mind cannot conceive them, though expressed in figures derived from accurate measurement. The nearest star to us is Alpha of the Centaur, near the Southern Cross. Its distance is, in fact, twenty-six million million miles away. And astronomers are dealing with stars estimated to be tens of thousands of times more distant, while those objects about which we can form no estimate must be immeasurably farther away. We look upon the sun as being inconceivably distant, though it is only 93,000,000 miles away. Yet its distance is almost as nothing compared with the other stars.

The stars are so prodigiously remote that their measurement has always been considered to be the most difficult of all astronomical observations of precision. It is also, in the present condition of our science, quite the most desirable.

A surveyor wishing to get the distance to an inaccessible peak, measures a base-line, perhaps a mile long, on the ground, and, using his theodolite, he measures the direction of the peak from each end of the base-line. He is then able to calculate the distance of the peak.

So long as the peak is less than, perhaps, a hundred times the length of the base-line he can thus get the peak's distance with fair accuracy. The farther away the peak is, the more difficult it becomes to be very accurate.

The astronomer who attempts to measure the distance of a star follows precisely the same general plan as the surveyor, although the distance of the star is appalling. He makes use of the very longest base-line available, from the two ends of which it is possible for him to make observations on the star's apparent direction. Such a base-line is given by two positions of the earth, in its annual journey round the sun, at an interval of six months. This base-line has the enormous length of 186,000,000 miles. If circumstances enable him to use only a part of it, his base-line still remains very enormous, though very small indeed compared with the distance he wants to measure.

In this manner three astronomers—Struve, Bessel, and Henderson—independently, and at about the same date (1832-1840), secured observations of three separate stars—Vega, 61 of the Swan, and Alpha of the Centaur—which, for the first time in the world's history, showed an apparent change of place of any star, due to the earth's changing place in its revolution round the sun.

It was Henderson, the Edinburgh astronomer, when observing the place of Alpha of the Centaur from the Cape of Good Hope in 1832-1833, who had the good fortune to select for his study that star which is still recognized as being the nearest of all stars in the universe. Later observers have bettered the observations, and we know with considerable accuracy that this nearest star is twenty-six billion (26,000,000,000,000) miles distant, or 280,000 times farther away than the sun. If the sun were at that distance we should see it with its brightness reduced in the ratio of 78,400,000,000 to 1. It would then shine only as a star of the third or fourth magnitude, like the smallest of the seven stars in the Plough constellation. It is a surprise thus to find that our brilliant great sun is only a common star, made to look so large and bright only by its nearness.

Such distances are beyond the power of our minds to conceive, and we have to seek some more convenient unit than a mile, or even than the sun's distance. Light travels over the prodigious length of 186,000 miles in a second of time. Anything that happens on the sun is not seen by us for eight minutes. In spite of its enormous speed, light takes all that time to travel from the sun to the earth. It will now become even more clear that the distance of the nearest fixed star is inconceivable when we know that light takes over four years to reach us from Alpha of the Centaur. This star is invisible from England, and the nearest star visible to us is Sirius, the king of stars, and light takes about nine years to reach us from him. This unit, the "light-year" (5,880,000,000,000 miles), is a convenient unit for comparing star distances. The length of a light-year is also 63,290 times the sun's distance from the earth.

The surveyor's method for measuring distances, just spoken of, is the only sure method that can be applied to the stars. A few hundred have thus been measured with a degree of accuracy concerning which we can say no more than that it is better than nothing.

Working upon these data, attempts have been made with some success to detect empirical relations between the star's distance, its magnitude, and its temperature as judged by spectrum tests (to be referred to presently, see pp. 46, 47). In this way the presumed distances of thousands of stars have been catalogued. Other indirect methods, founded upon fairly sound arguments, have been cordially welcomed in spite of their possible inaccuracies, because the want for this information is so exacting and so urgent.

By one of these methods Sir Frank Dyson, the Astronomer Royal, has found that the nearest stars are not concentrated in the Milky Way, but are fairly evenly distributed in all directions, and occupy a space like a flattened sphere, probably lying within that ring of space which is occupied by the stars of the Milky Way.

The Architecture of the Firmament.—The result of all the studies on these and similar lines by astronomers of to-day has been the pretty general acceptance of a working hypothesis. This is: That the stars in this stellar system, of which our sun is a member, are limited both in numbers and in extent; limited to a few thousands of millions; limited in extent within the boundaries of two distinct regions in space, the far-stretching, flat, ring-shaped galaxy, containing stars of the Milky Way, and the nearly globular space within that ring with our solar system situated near the middle of it.

Our firmament on this view is an island universe in realms of space which probably contain numerous other island universes of the same order of magnitude as our own.

The conclusion arrived at as to the architecture of our own firmament is itself sufficiently startling. There are thousands of people in northern latitudes who rejoice in the glory of a starry night who have never inquired about, perhaps never noticed, that faint white streak, the Milky Way. And now we are led to believe that the Galaxy, or Milky Way, is the fundamental basis of the architecture of the heavens. So it is with many who live in northern climes. Those, however, who travel to more southern regions of the globe form a different impression of the Milky Way, for they behold all the brilliant spectacle of the star-clouds of glory which constitute the southern portions of the Galaxy. Then they can be more ready to accept our Milky Way as the foundation upon which the firmament is built.

CHAPTER V

THE SPECTRUM OF A STAR

A RAINBOW is one of the most beautiful forms in which Nature (the name by which philosophers often allude to the Creator) presents an illustration of the poet's words:

> " 'Beauty is truth, truth beauty,' that is all
> Ye know on earth, and all ye need to know."

And the truth that we get from its beauty is this: the bow, with its centre in the opposite direction from the sun, and with all the spectrum colours—red, orange, yellow, green, blue, indigo, and violet, in that order—appears where rain is falling, while the sun is shining behind us. But the colours are not in the rain. The white light of the sun is sending its rays on to the raindrops. And its white light, when passing through the drop, is decomposed into all of these, its constituent colours.

Nature shows the same beauty, to illustrate a like truth, when a lamp falls on a surface of mother-of-pearl. That surface can be seen through a microscope to be covered with closely parallel striations, like scratched lines on its surface. The reflection of a lamp from that surface shows all the colours of the rainbow in order as before. The colours are not in the mother-of pearl, but in the compound white light of the lamp. In fact, if you take an impression of the mother-of-pearl in black sealing-wax, it also shows the same rainbow, or spectrum colours.

If a wedge of glass, large enough to cover the whole of a telescope's object-glass, be put in front of that glass, it bends the straight course of light from a star into a new direction, towards the thick edge of the wedge. And, to see the star, the telescope has to be pointed, it may be as much as thirty degrees away from the star. The image of the star in the focus of the telescope can then be examined with the eyepiece.

And this image is found to look no longer like a point of light, but like a streak of all the colours of the rainbow from red to violet. In fact, the star-image has been drawn out by the wedge into a linear "*spectrum*." The truth is that the different colours, of which the star's white light is made up, are all deflected, but each to a different extent—the red perhaps thirty, and the violet thirty and a half degrees.

Thus might the coloured spectrum of a star be examined. And we should find the continuous coloured spectrum broken at intervals, indicating certain colours in which the star's white light is deficient when that light reaches us from the star. The truth is that the vapours in the atmosphere of the star itself absorb certain colours of the star's white light. These missing colours in the light of each star form the chief point of interest when we examine a star's spectrum. These missing colours do, in fact, tell us what materials exist in the star's atmosphere. Iron, hydrogen, calcium, and any other chemical substances, when hot enough to be in the form of vapour, do absorb certain definite colours from white light that passes through the vapour, each material absorbing its own special colours. Some of them—iron, for example—produce thousands of breaks in the continuous spectrum of colours when examined with powerful optical instruments.

These breaks in the spectrum cannot be very well seen so long as the spectrum in the telescope's focus is only a linear streak variously coloured. An excellent plan for improving them is to use, as a special eyepiece, a lens not having a spherical, but a suitably chosen cylindrical surface. The spectrum then is perfect, and looks like a broad ribbon, red and violet at the ends, and with the other colours in proper order between. Colours that are missing in the light of the star are thus clearly indicated by lines across the coloured ribbon. The position, on the continuous coloured spectrum of a star's light, of each dark line can be measured, and compared with lines found in the spectrum of iron, hydrogen, calcium, etc., during our work with a spectroscope in the laboratory.

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The above ingenious device for showing the spectrum of a star, consisting of a wedge in front of a telescope's "object-glass," and a cylindrical lens in its "eyepiece," is one of the forms of "*spectroscope*" used by Father Secchi, at the Collegio Romano in Rome, when the art of spectroscopically detecting the presence of any chemical substance had just been discovered. That was in the sixties of last century, when

Secchi used it for cataloguing the various peculiarities in the spectra of a great number of different stars.

The same results can be attained by other instrumental equipments. Very commonly the prism which disperses, or separates out, the colours of which white light is made can be placed at the eye-end of the telescope. A complete independent spectroscope such as chemists use in their laboratories can thus be attached to the eye-end of a telescope.

Other astronomers imitate the action of mother-of-pearl by scratching upon a metal surface fine lines, thousands to each inch. This ruled "*grating*," when used as a reflector of the star's light, separates the colours into a spectrum.

For the most accurate work astronomers now employ photographic plates to produce what they call "spectrograms" of the different stars. The position of dark lines on these spectrograms can be measured at leisure with extreme precision.

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Spectrum Analysis—In the chemist's laboratory discoveries are made with a spectroscope; and then we make use of the same instrument directed to the stars. The light coming from a white-hot poker, or the carbon of an electric arc-lamp, or any other solid or liquid source of light, shows a spectrum continuous in brightness from the red end, through the orange, yellow, green, blue, and indigo colours to the violet end.

If, however, the source of light be so hot as to be neither solid nor liquid, but vaporized—as when sodium or common salt is put into a colourless flame of spirit of wine, or as when an electric spark passes from one iron wire to another—the spectrum is no longer continuous. Certain colours only are then sent out from the vibrating atoms of the vaporized material. Thus, with the simplest kind of apparatus, sodium is represented by a bright yellow line. With a refined instrument the presence of iron in a source of light is assured by the glowing of thousands of bright lines in well-measured positions on the spectrogram. So can the lines of all chemical elements be measured, if used instead of sodium or iron.

If, however, we use the low-temperature sodium vapour in conjunction with the high temperature of carbon in an electric arc-lamp, we can make an interesting experiment in the laboratory. And this experiment throws a flood of light on the meaning of what the spectroscope exhibits when pointed to the sun or to any other star.

Experiment.—The spectrum that we see, when looking through a spectroscope at the pure white and hot arc-light, is a ribbon of continuous colour from red to violet. This is the continuous spectrum that is shown by any very hot solid or liquid material, or even by a gas so much compressed as to bring its atoms very close together. If now the flame, containing the sodium vapour at a much lower temperature than the arc-lamp, be interposed in the path of white light from the arc-lamp, a dark line is seen to cross the ribbon spectrum at the yellow colour. The position of this line on the spectrum can be marked by a pointer. Now remove the arc-lamp. The continuous spectrum disappears and a bright yellow line is seen, exactly where the pointer is.

A refined spectroscope shows many lines besides the very bright yellow one. In this way every chemical substance has been examined in our laboratories, to measure the spectrum lines that belong to each chemical substance.

The astronomer observes the exact place on the spectrum of dark lines, in the light coming from the sun, or any star. The continuous spectrum in that light tells us that what we may call the *body* of the sun or star is a very hot solid or liquid substance, or else gaseous under enormous compression. The dark lines across the continuous spectrum tell us of what materials the sun's or star's cooler atmosphere is composed.

Thus have we learned that, in the sun's atmosphere, which is a star in the same region of space as our earth, there exist fully a half of the number of chemical elements that are known on our earth. Some of the other stars tell the same tale, while in the atmosphere of many other stars hydrogen seems to be the chief component. In others we discover a predominance of compound molecules of titanium, carbon, or zirconium.

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TEMPERATURE.—The spectrum of iron shows thousands of lines that are reproduced in the spectrum of the sun. Laboratory experiments have shown the spectrum lines of a substance to change their relative intensity with a change of temperature. Thus astronomers are beginning to know something about the temperature of a star's atmosphere. The temperature of the "body" of a star, the part which creates the continuous spectrum, is indicated by comparing the brightness of two parts—*e.g.*, red and green—of the star's light. The rules for getting the temperature from this comparison have been sought in our laboratories with some success.

RADIAL VELOCITY.—But perhaps the most surprising and fruitful of all spectrum discoveries remains to be told. If we find all the spectrum lines of some star to be slightly shifted in place, either towards the blue or towards the red end of the spectrum, then we know that the star is moving towards or from us. A shift towards *blue* means *approach* to, and towards the *red* means *recession* from us. And if we measure the amount of this shift, we know the speed, in miles per second, at which the approach or recession is being executed.

Thus we learn, by this truly marvellous power of the spectroscope, that our old friend Vega in the Lyre is approaching us at the rate of nine miles a second, while Capella, at the other side of the Pole Star, is receding from us at nineteen miles a second, and Rigel, the brightest star in Orion, at fourteen miles a second. This power of measuring "radial velocities" —*i.e.*, movements in our line of sight to or from us— is in complete agreement with what we know from theory about the manner in which light is transmitted through space (see also pp. 67-69).

CHAPTER VI

DIFFERENT TYPES OF STAR SPECTRUM

IT has been found that, while there are great varieties in the spectra of stars, these can, for the majority of stars, be divided into a small number of classes, distinguished by the materials most prominent in their atmospheres, as exhibited by the dark lines in their spectra:

Sirius and Vega and other very white stars exhibit more hydrogen than anything else in their spectra. Capella, like the sun, exhibits chiefly metallic lines, with calcium very marked. Betelgeuse in Orion's shoulder has some resemblance to the latter, but its spectrum is specially marked by dark bands, due to titanium oxide.

The attempts that have been made to estimate the temperature of these stars, at the surface which gives a continuous spectrum, make Sirius and Vega the hottest, perhaps 10,000° C. The sun and Capella would be about 6,000°. We cannot produce such heat artificially. Betelgeuse would be about 3,000°, a temperature so low that we can get it in our laboratories. These three types of spectra are called, by the Harvard College Observatory, Classes A, G, and M—A for Sirius, G for Capella, and M for Betelgeuse.

Stars like Rigel, found chiefly in the constellations

Orion and Carina, show helium added to the hydrogen of Class A, and are called B stars. Some stars can be found between the standard types A and G. They are called F stars; also some between G and M, and they are K stars.

Thus we have a continuous series of spectra:

$$\underbrace{\text{Helium}}_{\text{B}}\quad\underbrace{\text{Hydrogen}}_{\text{A}}\quad\underset{\text{F}}{}\quad\underbrace{\text{Calcium}}_{\text{G}}\quad\underset{\text{K}}{}\quad\underbrace{\text{Titanium Oxide}}_{\text{M}}$$

There are several other types of spectra. Their alphabetical names, as given by Harvard, are P, O, R, N, and S. These, however, rather militate against the most commonly accepted theory about spectral classes called the Lockyer-Russell evolution theory; and they have to be left out in any general statement of the theory.

The arguments in support of the theory have been so seriously discredited of late years, sometimes by the most determined supporters of the theory, that, in this noncontroversial book, it will be well merely to state the facts and the theory. And even so much is done only because at the present .period of our century this evolution theory is being very generally accepted by a majority of astronomers as a working hypothesis.

The most important fact which has been reached is that the temperature of the star's *body* (*i.e.*, the source of the continuous spectrum) rises regularly with each spectral class from M to B. Very possibly, the atmospheric layer wherein absorption of heat and light takes place may also follow the same law. This absorption is the cause of the dark spectrum lines indicating different materials—helium, hydrogen, calcium and metals generally, titanium oxide.

The next fact is the discovery by Campbell, of the Lick Observatory. All stars have some movement, and the spectroscope enables us to measure the radial velocity of each star. Campbell finds that the average velocity of the M stars, whether giants or dwarfs, is the greatest, over 11 miles a second, the A stars 8, and that of the B stars is the least, about 5 miles a second.

Another fact is that stars of certain spectral types are to be found chiefly in certain particular regions of space. Thus the B stars are mostly in the constellations Orion and Carina. The A stars are, most of them, in the Milky Way. Moreover, these are on the average at 2¼ times the distance of G stars. And about some other localizations of the spectrum classes there is no doubt whatever. Kapteyn estimated the average distance of B stars to be 29 million times the distance of the sun, of A stars 20 million, of F, G, and K stars 9 million, and of M stars 18 million times the distance from sun to earth.

The masses of the stars also seem to diminish regularly in the order of the spectral classes, from B to M.

THE EVOLUTION-HYPOTHESIS. — The Lockyer-Russell theory says that a star begins life as a cold nebula. It gets hotter and hotter as time goes on. [The source of the energy of stellar temperature is still a matter of dispute.] While getting hotter it contracts in size under its own gravitation. It first becomes luminous as a red *giant* M star, the diameter being far greater than that of the sun, and more of the dimensions of the planetary orbits. The temperature rises, and the size contracts until it has a density comparable to the sun. At this stage, if the star be of great mass, it is a B star. Those of less and less mass reach that density sooner, in the stage of Class A, F, G, or even K. Then the star begins to get colder and colder, and it passes through the spectrum classes in reverse order; returning to each class when its temperature has fallen to the condition belonging to that class. Finally it is so cold as to become invisible.

It follows that a very massive star goes through the spectrum-changes in the following order.

$$\underbrace{\text{M, K, G, F, A,}}_{\text{giants}}\ \text{B,}\ \underbrace{\text{A, F, G, K, M.}}_{\text{dwarfs}}$$

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When we know the distances of a good many stars, and their brightness as seen by us at those distances, it is easy to compare their *absolute brightness,* such as they *would* have *if* they were all at the same distance.

Hertzsprung did this. He found that for certain classes of stars, notably those of Class K, all the stars whose distances had been measured were in themselves either very large indeed or very small.

This is what must happen on the Lockyer-Russell hypothesis of evolution, and it was this fact that started H. N. Russell on the giant and dwarf theory.

The giant and dwarf theory has been developed in many ways since it was first propounded. But it ought to be noted how the great Dutch astronomers, van Rhijn, and also Hertzsprung, the discoverer of giants and dwarfs, demonstrate that there are in all probability stars of each class, intermediate in absolute brightness between the giants and dwarfs.

It should also be noted that Campbell, of the Lick Observatory, who discovered the decrease in star velocities from M to B as giants, and their subsequent increase in velocity from B to M as dwarfs, cannot reconcile this with the present hypothesis.

Nor must the forcible remark of Perrine, of the Mt. Wilson Observatory, be neglected: "The physical condition of a star is governed more by its 'locality' than by the age of its evolution."

In the present state of our knowledge, or of our ignorance, in this year of grace 1927, the true astronomer accepts all such theories not as truths of science, but as *working hypotheses* to guide us to new lines of research.

CHAPTER VII

PROPER MOTIONS OF STARS

THE first idea we ever have of the stars is that they are just points of light absolutely fixed in the sky, unchanging, perpetual signals, guides, and helps; placed there at the Creation to remain as they are till the Day of Judgment.

Already we have learnt that they are great big hot things like the sun, made of the same stuff as we find on the earth. Next, we come to learn that they are all in movement. The spectroscope tells us of their motion in our line of sight, what is called their "radial velocity." But long before that was discovered, their minute cross motions among one another had shattered the idea of immobility. People had been accustomed to call them *fixed* stars, to distinguish them from the planets or *wandering* stars. Now we know, by comparing old with modern observations of the positions of stars, that they are all in motion. These motions look to us very small because the stars are so very far away. They are most easy to discover among some of the nearest stars.

Halley, the illustrious Astronomer Royal of Newton's time, was the first to suspect this movement called "proper motion," among the other stars, of Arcturus, Sirius, and Aldebaran, in the year 1718. Arcturus is the bright, lonely star, to which the

Bear's tail, or the handle of the Plough, points (see Fig. 4, p. 10). Since the days when the old Greek astronomer, Hipparchus, measured the star positions, Arcturus has moved, among other stars in its constellation Boötes, over a distance actually amounting to two and a half times the apparent diameter of the moon. In the same time Sirius passed over one and a half diameters. But the wonder does not cease with that discovery. For the distance of Arcturus has been approximately found by observation; and this enables us to convert its *annual proper motion* of over two seconds of arc into a *cross motion* of so many miles per second. In this way it appears that Arcturus is travelling at the prodigious speed of 288 miles a second. Therefore, since Hipparchus measured its position, it must have moved over a distance of something like eighteen billion (18,000,000,000,000) miles; nearly as far as Alpha of the Centaur is from our solar system.

The field open to us for exploring the movement of stars is not now confined to this cross motion, or proper motion, but has been marvellously increased since we learned how, with the help of a spectroscope, to measure the speed of a star's motion, towards or from us, by a shift of the spectrum lines.

The greatest proper motion of any star, now known, is that of Barnard's star, called after the discoverer. This star passes over a space equal to the moon's diameter in the short time of only about 180 years.

Few bright stars have proper motions comparable with that of Arcturus or Sirius. Alpha of the Centaur and Vega, however, move very rapidly. The stars of smallest mass seem generally to have the greatest velocities.

We have now got catalogues of the proper motions of thousands of stars. It is interesting, if somewhat laborious, to mark them on a star-chart. Draw a pencil-line on the chart, from each star in the catalogue, with an arrow head to show the direction of its proper motion. Then make the length of this line from the star equal to the star's proper motion, on any scale we may have chosen, say one inch to represent an annual proper motion of one second of arc.

When this has been done, the picture presented by the little lines of proper motion takes a new meaning. The direction of the lines that have been drawn does not appear to be altogether fortuitous. There are signs, here and there, of groups of stars all with a common motion, both in direction and amount; small streams of stars. After looking at such a picture, the universe of stars acquires for us an entirely new character. It is no longer a stationary structure. It gives to us the notion of a flowing universe of interacting suns, some single, others together, whirling through space, over prescribed orbits for us to discover, over recognizable tracks, all guided and governed, in all probability, by the same forces of gravitation, cohesion, elasticity, chemical action, heat, and electricity, whose actions we upon this little world can study in our homes. Such a surprising and invigorating transformation and change of outlook, from a dry catalogue into a living picture, stirs a fine spirit of speculation in the heart of everyone who cares for the stars.

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It was by drawing for himself such a picture of stellar proper motions that R. A. Proctor found, in those stars of *Ursa Major*, which we call the Plough, one of the best examples of a group of stars all having the same proper motion. Five out of the seven bright stars that give an outline to the Plough (besides the less bright *Alcor*, close to *Mizar*, the middle star of the plough handle), were seen, on his chart, to be all travelling in nearly the same direction, and with the same velocity. And the slight differences almost disappear when we take account of perspective. Later, when the spectroscope was used for measuring radial velocities, towards or from us, these same stars were all found to be approaching us, and at not very different speeds.

A still more wonderful discovery was afterwards made about this *Ursa Major* star-stream. If we know the distance of a star from us, it is easy for a computer to find its exact motion in space from the observed proper motion and radial velocity. Unfortunately there are not many stars whose distance can be measured with sufficient accuracy for this purpose. One of these, however, is Sirius, the brightest star in the sky; and the discovery has been made that its motion in space is from the same point of the sky, the perspective "radiant point" of the group of six

Plough stars. Altogether, six stars in different constellations are suspected to be additional members of the *Ursa Major* star-stream, all going the same way as that stream, and at about the same speed. That Sirius, south of the heavenly equator, far distant from the stars in the northern Plough, should belong to the same group opens up a completely new conception of our own situation in the stellar universe.

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The Pleiades.—Let us make another call upon a family of old friends among the stars, to hear about their travels. On the west side of Orion is the somewhat ruddy Aldebaran, Alpha of the Bull constellation. It is one of the lighthouses on the ecliptic, the trade route of the planets. That route passes between Aldebaran and the lovely little cluster of stars still farther west, called the Pleiades. These Pleiades, a bunch of six to most people, and of eleven to really good eyes, are a very wonderful group in many ways. They are all helium stars, and they are, each of them, enveloped in nebulous streaky light of great extent. There used to be seven stars, not six. One seems to have been lost during historical times. When the proper motions of the six bright stars are looked at on the chart they all point in the same direction. The telescope reveals two hundred and forty-six stars in the cluster between the third and fifteenth magnitudes, all travelling in much the same direction at the rate of about five and a half seconds per century. We may now pass from this beautiful little nosegay of buds to an equally lovely double spray of starry petals.

The Hyades.—In the same part of the sky there is a beautiful little string of stars, V-shaped, with Aldebaran at one end of the V, called the Hyades. Our pleasure in noticing them is very much increased when we are aware that about forty of them, mostly telescopic, make up the most wonderful family of migrant stars as yet discovered, all streaming at the same pace in one direction. So accurately are they doing this that the effects of perspective are quite marked when we plot them, with their observed proper motions, on a large scale star-chart. The little lines on the chart are seen to point with wonderful exactness to the radiant point, towards which they are all flying, the lengths of lines nearest to that point being rather shorter than those farther from it. This is all quite in accord with the laws of perspective. The radial velocities as found by the spectroscope confirm this truth.

These stars, at their present distances from us, are ranked as of the third to the seventh magnitudes and cover fifteen degrees. In the distant future, after sixty-five million years shall have elapsed, Professor Boss calculates that this cluster will be condensed so as to cover not more than one-third of a degree, with the stars reduced to the ninth to twelfth magnitude.

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Solar Motion.—Soon after a small number of proper motions had been measured, in different parts of the sky, a general tendency was evident for their apparent courses to radiate or diverge from a spot in the region of Vega, Alpha of the Lyre constellation, or from some point in the neighbouring constellation *Hercules*. [Naturally, the stars whose proper motions show this effect to the greatest extent are the stars which lie in the region about ninety degrees from Vega.] The fact is now quite well established. Does this mean a general tendency of all stars to move in one direction—away from Vega? Or does it mean that our solar system is moving towards Vega? The effect would be exactly the same on either supposition, and we cannot ever detect absolute motion, only relative. But the simple motion of only one star, the sun, is certainly the clearest expression of the observed facts.

The power of the spectroscope in telling us the speed with which a star is approaching or receding from us has also been applied to get the direction and amount of the solar motion. The result has always been to show that the stars near Vega are all approaching us, while those at the opposite part of the sky are receding. This discovery confirms beautifully and perfectly the general result already derived from proper motions. This is doubly satisfactory, because the stars that are most effective in showing this solar motion by radial velocities are those near the line going to Vega; while the stars most effective with proper motion are on the circle of stars round us, which are ninety degrees away from Vega. In fact, it follows that two totally different sets of stars give *very nearly* the same direction for the solar motion. The spectroscopic method, however, has this advantage. It tells us the actual velocity of the sun's motion among the stars, towards Vega. It is about fourteen miles a second—that is to say, a little quicker than the motion of our earth round the sun.

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THE TWO STAR DRIFTS.—After the question of the solar motion had been worked out so well, by taking the *mean* proper motions or the *mean* radial velocities of many stars in each part of the sky, the question arose as to the *individual* motions that go to constitute the mean. Are these individual motions of the stars entirely at random? Or, do the stars themselves drift to any extent in swarms independent of solar motion?

The latter supposition seemed likely from the fact that when we take several particular classes of stars, we do not get quite the same result for the solar motion. Notably, the stars lying near to the line of the sun's motion indicate by their radial velocities a solar motion to a direction southward of that given by proper motions of those stars lying in the plane at right-angles to the solar motion. This indicates that the stars in line with Vega have a small mean motion of their own in a northerly direction relatively to the other stars.

Eventually, the theory of drifting in swarms was demonstrated, and in an unexpected form, early in the present century, by that brilliant successor to the methods of Sir William Herschel, Professor Kapteyn of Leyden, Holland.

He found that the mean proper motions of stars in different parts of the sky are not accounted for by a solar motion alone. They are, however, extremely well accounted for by *a solar motion in one direction towards Vega, combined with a general drifting of the stars, one lot of them in a direction inclined at forty-six degrees to the solar motion, and the others in exactly the opposite direction.*

This two-drift theory of stellar motions is one of the grandest generalizations ever made in sidereal astronomy. It has been derived, however, from the proper motions of stars near enough to us for exact measurement. It need not apply to very distant stars or to the whole stellar universe. It may be local to our part of it.

Be that as it may, we can rejoice at the splendid start which has now been made in the exploration of the necessarily complex system of local movements among stars, of individuals, small groups, and enormous crowds, in the near regions of our vast stellar universe.

CHAPTER VIII

DOUBLE STARS

Among the many new stellar discoveries made by the invention of the telescope, from the year 1610 onwards, it was found that stars which look single to the naked eye are often in reality double stars, a very close pair. The first discovery of this kind was Mizar in the tail of the Great Bear, by Riccioli about 1650. Soon afterwards a star in the *Ram* constellation, Castor in the *Twins,* and Gamma of the *Virgin,* were added. Huyghens, in 1656, found Theta of Orion, in the middle of the great nebula or luminous cloud, to consist of three distinct stars all very close together. Many more were added in the eighteenth century; so many, in fact, that the opinion arose that these double stars are not merely in the same direction, and still separated by enormous distances in the line of sight, but that they are really close together in space and physically connected.

In the nineteenth century the spectroscope provided us with a new power, to be described presently, of detecting double stars, although they look single even in the most powerful telescope.

And to-day, in the twentieth century, the opinion prevails that at least one out of every four or five stars in the whole firmament is double.

Some double stars can be seen even without the aid of a telescope. Mizar is the Arabic name for the middle star in the tail of the *Great Bear*. A companion star, called Alcor, can be seen close to it with the naked eye. In a telescope they are too far apart to be classed as double star. But Mizar itself is a true double star, the first that was ever discovered, as already stated.

Beside our friend Vega, overhead of a summer night, are two little stars forming with it a regular triangle. One of these is *Epsilon* of the Lyre. When attention is fixed upon it, no telescope is required to see that it is double. Even if not seen separate by some eyes, they look like an elongated star, owing to the double character. An opera glass will make this quite clear. The wonderful part of the story is that a moderate telescope shows each of these two little stars of which *Epsilon Lyræ* is composed to be itself double.

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COLOURED DOUBLE STARS.—A study of double stars is a favourite starting-point for the young astronomer. And his interest in them is increased by the beautiful contrasts of colour often displayed by such a pair of gems. Moreover, the close double stars form one of the finest tests of the performance of a telescope; and in this way amateurs get a new zest to their hobby in comparing the performances of rival telescopes.

To give a single example of striking colours in double stars a telescope may be directed to that beautiful object, Gamma of Andromeda. It is easy to find towards the close of the year, when the great square of

Pegasus is conspicuous in the southern sky (see Fig. 2, p. 9). Three bright stars run in a straight line from the north-east corner of the square to Persius. These three stars lie beneath the west of Cassiopeia. They are the three brightest stars in the constellation *Andromeda,* and the third one is *Gamma.* A moderate telescope shows it to be double, a large orange star and a smaller emerald-green one. A more powerful glass resolves this last one into two, one blue, the other yellow. This is one example of many multiple-coloured suns that give delight to all who start upon the exciting sport of hunting up double, and multiple, and coloured stars, with the help of a telescope, a guide-book such as Webb's, and, perhaps best of all, an experienced friend.

When we have the good fortune to see through a telescope these sparkling gems, the imagination is apt to run riot about any inhabitants of any planets that may belong to these suns. There the supposed human beings would live in a magical world of colour, where the red sun sets, and a blue or emerald sun remains shining upon the world, as when we see a landscape through blue, orange, or rose-coloured glasses.

During the time that a blue sun is eclipsing a red one, what weird alternations of colour may transform the aspect of a country scene! On such a planet there may be long periods with no darkness of night. For twelve hours a sun may have flooded the outer world and the interior of the home with rose-coloured tints, and after it sets there may follow twelve hours of green light from another pair of suns, one blue, the other yellow. Then a moon may pass and eclipse one or other of these, leaving people in a world of blue or yellow light. That moon itself may be lighted by the two or three suns, and may show varying tints of combined colours over different parts of its surface. Then, again, how inconvenient must it be to have to do with both "red solar time" and "blue solar time" at the same hour! And yet, if there be people to see these things, they probably accept them as being what ought to be expected, rather than as a heavenly wonder.

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SOLAR SYSTEMS AMONG THE STARS.—Sir Isaac Newton proved the law of gravitation to be universal in the solar system. Its action is manifested not only by the weight of things we handle, attracted towards the centre of the earth, but specially by the revolution of bodies round each other, as the planets revolve round the sun, or the moon round the earth, in the solar system.

It was reserved for Sir William Herschel, in 1803 and 1804, after thirty years of painstaking measurements, to extend the range of Newton's law, to state positively the splendid result of a comparison between his earlier observations of double stars and those made by him twenty years later. He found unmistakable proof that in many cases the pair are revolving round their common centre of gravity. This happens *under the same law of gravitation as that which holds the solar system together.* He gave even rough approximations to the periods of revolution. In the arch of bright stars framing the constellation of Orion (Fig. 1, p. 5) the twins Castor and Pollux are conspicuous. Castor is the one nearest to Capella. To this star Herschel gave a period of 342 years. The head of the *Lion* constellation (Fig. 3, p. 9) has a string of stars tracing the shape of a reaper's sickle. The brightest of those in the blade of the sickle is *Gamma*. It is a double star, and Herschel gave to it a period of 1,200 years.

In 1830, Savary published the mathematical formula for computing the true orbit of a binary pair of stars, and applied his method to one of Herschel's binaries in the toe of the *Great Bear*. Thus Xi of Ursæ Major was the first source of positive evidence that Newton's law extends beyond the solar system to the stars. It was a glorious achievement.

Herschel was followed in this study by the painstaking William Struve. He published a catalogue of about 3,000 double stars from an examination of no fewer than 120,000 stars. All double stars are not binary stars like those discovered by Herschel. That term is used only for a pair revolving round each other under the action of gravity, forming, in fact, solar systems among the stars. There is no evidence, however, for or against the existence of any family of small dark *planets*, like ours, illuminated by, and revolving round, these distant suns. The number of known binary stars is to-day very great.

Castor and Pollux in the northern skies have their counterpart to our antipodean friends in Alpha and Beta of the Centaur, an even more brilliant couple than the twins, pointing to the Southern Cross. Of these, Alpha resembles Castor in being double, and both stars of which it is composed are very bright. Halley discovered its double character in 1689. Its period is eighty years, and the pair have been followed through three revolutions in their elliptic orbit round each other. They are nearly equal in size. The brighter one resembles our own sun very closely in mass, brightness, and probably in temperature, and seems to be made of the same materials.

It is a wonderful consequence of Newton's law of gravitation that *we are actually able to weigh these binary stars* from a knowledge of their period of revolution, their separation apart, and their distance from us. As a general rule it has been found, in the limited number of cases where the distance has been measured, that most stars in the binary systems are of the same order of mass as the sun. Some may be ten times as massive, exceptional ones even more.

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SPECTROSCOPIC BINARIES.—The discovery of solar systems among the stars, controlled like our solar system by the force of gravitation, has been vastly expanded during the last thirty years. This has followed from the new power given to us by the spectroscope.

That instrument was first applied to the stars in the hope of finding what materials known to us on the earth are also present in different stars. This side of the question has made great progress, but the facts have been somewhat obscured by their interpretation, according to conflicting hypotheses.

The secondary results of applying a spectroscope to the stars is even more wonderful, and is now free from controversy, and tells us, with astronomical precision, *the rate at which any star is approaching us or receding from us*. And the spectroscope actually measures these velocities in miles per second. How can this be done?

Sound is transmitted to our ears by vibrations through the air. Light is transmitted to our eyes by vibrations through the all-pervading ether.

The pitch of a musical note is higher as the air vibrations succeed each other more rapidly. Low notes slower, high notes faster. The colour of a line in the spectrum of a star is farther towards the blue end of the spectrum as the ether vibrations succeed each other more rapidly, red vibrations slower, blue ones faster.

If the source of sound, or of light, is approaching us, the ear or eye catches more vibrations in a second than when it is at rest. So the pitch of a note is raised when approaching, as also it is lowered when receding. So also the colour of a spectrum line is shifted towards the blue end of the spectrum when a star is approaching us, as also towards the red end when receding. For the case of sound we have a good illustration, thus:

If you are standing at a railway station when a whistling locomotive dashes through the station, then, at the moment when it passes you, the pitch of its whistle is lowered, it may be as much as an octave. Take notice of this when you get the chance.

For the case of light, if we point a spectroscope to the sun, at its centre, its east edge, and its west edge, we see the spectrum lines of the east side shifted to the blue, and of the west side shifted towards the red; because by the sun's rotation on its axis the east side is approaching us, and the west side receding.

The Harvard College Observatory, U.S.A., with very moderate equipment, during the directorship of the late E. C. Pickering, started new and original lines of research, and did supply the world with some discoveries of first-class importance to astronomy. One of the greatest had to do with Mizar in the tail of the *Great Bear,* the first double star known, as already told, also the first double star to be photographed. In 1889, Pickering announced a discovery by his assistant, Miss Leavitt. She found that the dark lines in the spectrum of the brighter of the two stars of which the visual binary, Mizar, is composed, are double at regular intervals of time, and single between times. The double spectrum proves that the light comes from two separate stars, so close together as to look like one, and that one of them alternately is approaching or receding from us while the other is receding or approaching, giving a double shift of lines. In the intervals, when they neither approach nor recede, there is no relative shift of lines. They remain single.

Clearly the two stars are revolving round each other, alternately approaching us. When one star is at its greatest distance from us and the other at the least distance, their movement is all across the line of sight. There is no shift of spectrum lines, and these lines look single.

Finally, it was shown that the two stars of Mizar revolve round each other once in three weeks, that their distance apart is about the same as Mercury's distance from the sun; and lastly, that their combined mass is twenty times that of the sun.

Miss Leavitt's discovery has opened up a new branch of astronomy, and numerous "spectroscopic binaries" are constantly being added to the list.

The very first stars in which the spectrum lines were found to be periodically doubled, after Mizar, were our old friends Capella and her bright neighbour Beta of the same constellation, Auriga the Charioteer. None of these spectroscopic binaries has been seen as a double in the telescope. During the present decade, however, the invention of a new method for testing and measuring very close doubles has been entirely successful in the case of Capella, and every astronomer rejoiced at the confirmation, thus established, of the spectroscopic discovery.

Sometimes one of the two revolving stars of a spectroscopic binary is non-luminous. In such cases the spectrum lines are not doubled, but their periodical alternate shift to red and blue proves the existence of the invisible dark companion attracting the luminous body. Spica in the Virgin (Fig. 4, p. 10) was the first star thus found to have a dark companion.

CHAPTER IX

VARIABLE STARS

WE have now discovered that the stars are very far from being merely fixed points of light, which is the impression natural to a first outlook. They are all in motion.

There is one more important feature by which a certain individuality is shown among the stars. Many stars are constantly undergoing changes in brightness, some periodically at regular intervals, others with every conceivable degree of irregularity. The range of brightness may be very small and may take a long time to be accentuated. In other cases their brightness may change, from invisibility in a good telescope, to a rivalry with some of the brightest stars in the heavens, in the course of a day or two.

IRREGULAR VARIABLES, AND NEW STARS OR "NOVÆ."—It becomes less and less possible, with the modern great increase in the number that are discovered, to separate these two classes of variables. A "new star," or *Nova,* burst forth in 1918 in the constellation *The Eagle.* It was one of the brightest of the number, some thirty in all, that have been seen with the naked eye in historic times. Previously, it had been a variable star of the eleventh magnitude. It attained almost the brightness of Sirius in a few days, and then slowly faded away; and now it shines once more a faint variable star, as before its great outburst. The wild erratic changes in its spectrum were astonishing. This passed from being a continuous spectrum with dark lines, in a few days, to a spectrum of luminous bands due to hydrogen, indicating vortical movement. And these two spectra were often seen together. The dark lines of hydrogen, when compared in position on the spectrum with the bright bands of hydrogen, indicated the presence of two different bodies, with different velocities in the line of sight. The dark lines were shifted towards the blue end of the spectrum to an extent that indicated a velocity of approach towards us at the rate of some 2,000 miles a second compared with the bright bands of hydrogen.

In every one of these features Nova Aquilæ, 1918, went through phases commonly observed in all the *novæ*. No complete theory has as yet accounted for all the facts. The dual character, indicated by the spectra of two bodies, one of which moves rapidly compared with the other, has brought forward an explanation suggested by the luminous shooting stars and fireballs. These fly across the sky through the atmosphere, heated to incandescence by air friction, showing a continuous spectrum, while their trails of glowing gases are stationary in the atmosphere.

This theory of the outburst of a nova, like all of them, is still incomplete, but is perhaps the most likely one to prevail. It pre-supposes a collision between a star and one of the gaseous masses that are called nebulæ. These gaseous clouds frequent the

Milky Way, as do also the new stars. The gaseous friction would certainly heat the star and leave a glowing gaseous trail, just like a fireball. And gaseous nebulæ have been found surrounding new stars.

This is not the place to discuss the merits and defects of imperfect hypotheses. The gas friction theory is mentioned here because it may apply equally to new stars and to the next class of variables.

* * * * *

IRREGULAR VARIABLES.—The most typical irregular variable is *Eta* of *Carina* in the southern hemisphere. Its history also is the most extraordinary of all. At present a telescope is needed to see it, because, for a great many years, it has not been shining brightly. But, with a telescope it is seen beautifully situated in the middle of a wonderful cloud-spot, or gaseous nebula, which is spread out into a map of strange forms of glowing gas, called the keyhole nebula. Many of the irregular variables are thus seen to be associated with nebula, as are some "new stars." This fact leads us naturally to adopt, temporarily, at least, for want of a better one, the gas friction theory equally applicable to *new stars* and *irregular variables*, both of which brighten up when traversing the nebula.

The history of the most remarkable "irregular variable," Eta Carinæ (formerly known as Eta Argûs), so far as known, is this. In 1677, Halley saw it of magnitude 4; in 1687 it was magnitude 2; in 1751

Lacaille's observation was 2; from 1811 to 1815 it was 4; in 1827, it was of first magnitude. In 1843 it was −1, nearly as bright as Sirius. It fell off till 1870. Since then it has fluctuated about the seventh or eighth magnitude. All this is compatible with the resistance offered to the star's passage through dense and less dense parts of the great Argo nebula. But that is only an hypothesis *pro tem.*

The new star in the southern constellation Pictor, discovered in 1925, is intermediate between a nova and a variable. It was found in old photographs to have a magnitude 12 or 13, from 1889 to 1925. On April 13 in that year its magnitude was 3. It was not discovered until six weeks later. From May 28 to June 9 it brightened from magnitude 2·6 to 0·9. After June 20, in some months, it fell to third magnitude or thereabouts, and then fell off still more in brightness.

Its spectrum, and that of many new stars, resembles the spectrum of Eta of Carina, the great irregular variable star.

* * * * *

LONG-PERIOD VARIABLES.—There is no department in astronomy towards which amateur societies, like the British Astronomical Association, contribute so much in the way of continuous observation as that of long period variables. This class includes all the variable stars that were first discovered centuries ago, except *Algol*. The first was by Fabricius, in 1516. His variable star is *Omicron* in *Cetus* the whale, often called *Mira Ceti* (the wonderful). It is generally invisible to the naked eye, but is bright for three months in the year, sometimes rivalling Aldebaran. The variable stars of this class have periods (the interval of time from maximum to maximum) varying in different stars from 80 to 500 or 600 days. All other regular variables have periods not greater than a few days.

It is remarkable that this type of star is more surely detected by its spectrum than by its period. They all belong to the M stars, and their spectra all show some *bright* hydrogen lines, forming a subclass Md. Every known Md star is a long-period variable, and 85 per cent. of long-period variables have been proved to be Md stars. About 400 of them are known.

* * * * *

Delta Cephei Variables.—Short period variables, called after the fourth magnitude star Delta of *Cepheus* form a numerous class. This star, at intervals of five days and eight hours, brightens almost to third magnitude. Then it falls off for four days, after which it brightens rather suddenly. There is a large number of these delta cepheids, found mostly in the Milky Way.

Cluster Variables.—There are in certain sections of the sky about eighty small telescopic "*globular clusters*" of minute stars in which large numbers of short-period variables have been found having all the characteristics of Delta Cephei; except that the *period* is generally only a fraction of a day. This remarkable discovery was first made by Bailey in regard to the globular cluster *Omega* of the *Centaur*. He found, not only more variable stars in that cluster than were already known in all other parts of the heavens, but that all of them had the same period of about half a day.

ALGOL VARIABLES.—*Persius* constellation is the string of stars that passes from Cassopeia to the Pleiades. The two brightest stars are Alpha and Beta, generally about equal in brightness, of magnitude 2. Beta, a little to the right of the string of stars, is called Algol (Arabic for the Demon). It really consists of two stars, one bright, the other dark. They revolve round each other; and every three days or so the bright star of the pair is partially hidden or eclipsed by the dark one (which is about equal to it in size), and its brightness is reduced to one quarter, for about twenty minutes. In about three and a half hours it again reaches the second magnitude, which it retains for two and a half days.

The Algol variables all go through the same kind of changes with incredible punctuality. The hours of minimum brightness can be safely predicted years ahead. There are some, like Beta of the *Lyre,* where the companion is not dark. For this reason, twice in each revolution of the pair, we see only the light of one star instead of both, and so we see two minima in each revolution.

CHAPTER X

THE FRIENDSHIP OF THE STARS

EPILOGUE.—The author has now concluded a brief account of some of the marvels which are the daily bread of astronomers in their study of the stars. The reader ought now to know how to make a personal acquaintance with many of these objects of his admiration.

An attempt has been made in this book to enable him to take note of, and to understand, the varying characters of different stars, and to transform his mere acquaintanceship, and recognition of them, into a real personal friendship.

Let anyone who has read these pages, and who has identified in the sky many of the stars described, recall everything that he now knows about the individual character of each of the following stars: the splendid Sirius, the steel-blue Vega, the golden Capella, Mizar, Betelgeuse, Mira of Cetus, Algol, Alpha and Omega of the Centaur, Arcturus, Spica, the star groups of Pleiades and Hyades beside Aldebaran. If then he does not feel his heart beat a little quicker, when one of these old friends, or a blazing planet, comes into view, and when he describes its marvels to the companion of his midnight stroll, then it must be confessed that the purpose of these pages can only have been partially attained. If, on the other hand, the reader can now see more clearly the wonder and the glory of the stars, then it may be hoped that the friendship of the stars may likewise become to him a reality and a pleasure. *Vale.*

BIBLIOGRAPHY

H. R. Gall and A. Inglis: *Easy Guide to the Constellations*. (Gall and Inglis.)

Sir Robert Ball: *Story of the Heavens*. (Cassell.)

Hutchinson's *Splendour of the Heavens*. 2 vols. Edited by Rev. T. E. R. Philips and Dr. W. H. Stevenson. (Hutchinson.)

Professor George Forbes: (1) *The Wonder and the Glory of the Stars* (Benn); (2) *History of Astronomy* (Watts).

Professor Herbert Dingle: *Modern Astrophysics*. (Collins, Sons and Co.)

Miss Agnes Clerke: *Popular History of Astronomy in the Nineteenth Century* (Black.)

For a deeper study, the following books should be read:

Robert Grant: *History of Physical Astronomy* (Baldwin.)

Sir George Airy: *Six Lectures on Astronomy*. (Simpkin and Marshall.)

Sir John Herschel: *Outlines of Astronomy*. (Longmans, Green and Co.)

H. N. Russell, R. S. Dugan, and J. G. Stewart: *Astronomy*. (Ginn and Co., New York.)

Also Norton's Star Maps or Atlas.

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ASTROPHYSICS

THE CHARACTERISTICS AND EVOLUTION OF THE STARS

By

W. M. SMART, M.A., D.Sc., F.R.A.S.

John Couch Adams Astronomer in the University Observatory, Cambridge

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TO

JACK AND ALASTAIR

WHOSE YOUTHFUL MINDS ARE STRUGGLING WITH
THE MYSTERIES OF THE UNIVERSE, THIS BOOK IS
AFFECTIONATELY DEDICATED

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ASTROPHYSICS

CHAPTER I

THE CHARACTERISTICS OF THE STARS

In Astrophysics we study the nature of the light and heat which reach us from the stars. Our observations are the clues by which we are led to investigate the nature of a particular star, the differences between the various classes of stars—and the circumstances which operate to produce these differences—the behaviour of matter under conditions which have not hitherto been imitated on the earth, the nature of the nebulæ and many other problems of surpassing interest. In this introductory chapter we shall consider briefly some of the characteristics of the stars.

In the first place, the stars are self-luminous bodies like the sun, and unlike the planets which are visible only by reason of the reflection of the sun's light from their surfaces. The sun, in fact, is a star—a very ordinary star, as we shall see later; its supreme importance as regards terrestrial life in all its forms is simply due to its comparative nearness to us. The stars are not alike in brightness, a fact of which even the most casual observer of the heavens is unerringly aware. On a clear night between two and three thousand stars are visible to the naked eye, ranging in brightness from the glorious Sirius to the faint objects just perceptible to the unaided vision. The smallest telescope will reveal thousands more; the faint stars visible in the great telescopes are to be counted in millions. Two thousand years ago Hipparchus recognised the desirability of grading the stars according to their apparent brightness. He divided the naked eye stars into six classes; the brightest stars (about a score in number) were assigned to the first class—they were designated "stars of the first magnitude," and so on until in the sixth class were the feeblest stars visible to the naked eye. This classification is, of course, very rough, and takes no account of the differences between the stars of the same magnitude class; for example, Sirius and Capella are both stars of the first magnitude, but actually Sirius appears considerably brighter than the latter. With modern instruments it is possible to measure with high accuracy the ratio of the apparent brightness of any two stars and so to give greater precision to the meaning of *magnitude* used in this connection. A typical first magnitude star is defined to be 100 times brighter than a typical sixth magnitude star—that is to say, the amount of light which reaches us from the former is equivalent to the amount of light from 100 stars each of the sixth magnitude. This is the principle connecting magnitude and the relative brightness of the stars. The fainter the star the larger is the number expressing its magnitude; a difference of 5 magnitudes corresponds to a brightness-ratio of 100 to 1; a difference of 1 magnitude to a brightness-ratio of a little over 2½ to 1. When the ratio of brightness of any two stars has been measured, the difference in magnitude can then be calculated. If any one star is arbitrarily assigned a number expressing its magnitude, then it follows that the magnitude of any other star can be found from the observed brightness-ratio. On the scale adopted, the magnitude of the bright star Spica, for example, is denoted by 1·2; as the bright star Capella is found to be 2½ times *brighter* than Spica, the magnitude of Capella is thus 1·2 *minus* 1—that is 0·2 (since the brightness-ratio of 2½ to 1 corresponds to a magnitude difference of 1). Sirius, the brightest star in the sky, is about 5¼ times *brighter* than Capella, and as this brightness-ratio corresponds to a difference of magnitude of 1·8 (this is found by calculation), the magnitude of Sirius is thus 0·2 *minus* 1·8 or −1·6. If Capella is 100 times brighter than another star, the magnitude of the latter is 0·2 *plus* 5·0—that is 5·2 (since the brightness-ratio of 100 to 1 corresponds to a magnitude difference of 5). The faintest stars visible in the largest telescope are of the 19th magnitude approximately; thus Sirius appears roughly about a hundred million times brighter than the feeblest stars ever seen. These examples are perhaps sufficient to indicate the relation between the relative brightness of the stars and the scale of magnitude.

The relative brightness of two stars can be estimated by eye at the telescope or more accurately by optical appliances into the details of which we need hardly enter. The magnitudes deduced from these measures are called "visual magnitudes." But it must be emphasised at this point that a bright star only *appears* to us to be brighter than a faint star, and we cannot tell, without further information, whether the bright star is really a more luminous star than the faint star or not. For example, Capella appears to us to be 2½ times brighter than Spica, but may not this be due, wholly or in part, to the greater remoteness of Spica from the earth? For this reason the magnitudes of the stars derived from the direct observations of brightness-ratio are called *apparent magnitudes*.

One of the greatest scientific achievements of the nineteenth century was the first measurement of the distance of a star. The principle involved may be simply illustrated as follows. Hold up a finger vertically and, with the right eye closed, note the object in the room which the finger appears to cover. Keeping head and finger steady, again note, with the left eye closed, the object which the finger now appears to cover. It will be seen that there is a marked change in direction, relatively to the objects in the room, of the finger as viewed by the left eye and by the right. In the course of a year the earth describes around the sun a mighty orbit with a diameter of 186,000,000 miles. On January 1, for example, we view the stars from a particular point of space; six months later, on July 1, the earth has moved around to the opposite side of the sun, and we now view the stars from a different point of space. In our illustration these two points correspond to the right and left eyes. The stars are at varying distances; let us suppose that there is one star very much nearer than the others; the near star is our finger and the very distant stars the more remote objects in the room. Just as the direction of the finger alters with respect to the objects when viewed by the right eye and by the left, so the direction of the near star with respect to the distant stars alters when observed on January 1 and on July 1. This may perhaps be made clearer by means of Fig 1, which shows the position of the earth, on January 1 and July 1, in its yearly path round the sun. The early observations made successfully ninety years ago by Bessel, Hend[illegible]son, and Struve were all visual observations. To-day the measurement of stellar distances, according to the principle just described, is undertaken by the photographic telescope. This method of measuring the distances of the stars is, essentially, similar to that of the land surveyor; it is known as the "trigonometrical method."

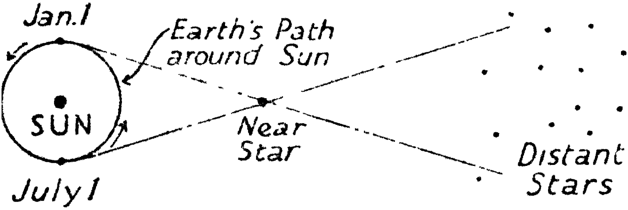

Fig. 1.

Stellar distances are so stupendous that the familiar units of length (*e.g.*, the mile) become wholly unsuitable. The astronomical unit of length is the average distance of the earth from the sun—namely, 92,900,000 miles. Expressed in terms of this unit, the nearest star is about 275,000 astronomical units distant from the sun. Clearly, even this unit becomes too unwieldy, and so a new unit, called the *parsec,* has been introduced. One parsec is defined to be 206,265 astronomical units; it is equivalent to 19 million million miles approximately. There is another unit in common use called the *light-year.* It is known that light travels with the amazing speed of 186,000 miles per second. It is an easy matter to calculate how far light will travel in a year—this distance is the light-year. Another simple calculation shows that 1 parsec is equal to 3¼ light-years. In this book we shall generally describe stellar distances in terms of light-years. The nearest star (Alpha Centauri)—in the southern sky—is about 4½ light-years away. This means that the light, which enters our eye at a particular moment, has taken 4½ years in its long journey through the emptiness of space to reach us from the star. The most remote objects whose distances have so far been measured are two of the great spiral nebulæ; their distances are close on one million light-years; we see them not as they *are* to-day but as they *were* nearly a million years ago.

It is tempting to tarry here and let the imagination dwell on the vastness of the universe revealed by modern astronomy; in our brief reference to the subject of stellar distances we have had a more precise object in view. We have seen that the measures of apparent magnitude tell us nothing more than that some stars *appear* to us to be brighter (or fainter) than others. If they all happened to be at the same distance from us the situation would be different, for we could then say, for example, that Capella is really and truly 2½ times more luminous than Spica, just as we might infer, standing some distance away, that the headlight of a motor car was 2½ times brighter than the sidelight of the same car. But when we know the distances of the stars we can calculate how bright they would appear to be if placed at any given distance from us. For example, if there are two stars, identical in every particular, one at a distance of 20 light-years and the other at a distance of 200 light-years, one would appear 100 times brighter than the other, so that their apparent magnitudes would differ by 5. In the same way, if Capella were removed to a distance equal to 10 times its present distance from the sun, it would appear as a star of magnitude 0·2 plus 5·0—that is, 5·2. In order to compare the luminosities of the stars, we require to know how bright they would appear if placed at some definite distance from the sun; the distance chosen by astronomers for this purpose is 10 parsecs or 32½ light-years. Knowing the distance of any star and its apparent magnitude we can now calculate what its magnitude would be if it were placed at this standard distance; such magnitudes are called *absolute magnitudes*. By means of their absolute magnitudes we can arrange the stars in order of intrinsic brightness—a most important characteristic of a star. The stars vary, in this respect, in the most astonishing way. Some are orbs of amazing brightness, beside which the sun would be as a glow-worm compared with a powerful searchlight; others are of such feeble luminosity that the sun itself would be equivalent in light-giving power to hundreds or thousands of these intrinsically faint stars. Let us consider one or two examples. Rigel, one of the brightest stars in the constellation of Orion, is of apparent magnitude 0·3; if it were at a distance of 32½ light-years, its magnitude (that is, the absolute magnitude) would be −5·6. The absolute magnitude of Capella is found to be − 0·6. The difference in these absolute magnitudes is exactly 5; this means that Rigel, which appears in the sky to be just a little fainter than Capella, is actually equivalent as a light-giving source to a hundred stars each of the luminosity of Capella. If the sun were removed to a distance of 32½ light-years, it would appear as a faint star of magnitude 5·0; compared with Capella, the sun is thus a feeble star; compared with Rigel, it is as a candle beside a powerful searchlight.

The very luminous stars, such as Rigel and Capella, are called *giants;* feebly luminous stars, such as the sun, are called *dwarfs.*

Another characteristic, which a careful observer of the heavens can readily detect, concerns the colour of the stars. Some stars, such as Betelgeuse, are of a richly red hue; stars such as Vega are white, and stars such as Rigel are blue. A very beautiful object in the telescope is the double star Gamma Andromedæ; one component is yellowish-white, the other strikingly blue. Every amateur photographer knows that red light has very little effect on the ordinary photographic plate; it might then be inferred that if two stars of the same apparent visual brightness, one blue in colour, the other red, are photographed with equal exposures on the same plate the character of the two images of the stars will be considerably different. What is found under these circumstances is that the image of the blue star is very much larger than that of the red star. Now the sizes of stellar images give an indication of the relative "photographic brightness" of the stars; the larger the image the brighter is the star as regards the kind of light which influences the photographic plate. From the measures of the stellar images the stars can be graded on a magnitude scale, similar to that adopted in visual observations; the magnitudes derived in this way are called *photographic magnitudes.* It is evident that some convention must be adopted with respect to the numbers signifying the visual magnitude and the photographic magnitude of one definite colour-class of star; the convention adopted is that for stars of the colour of Sirius and Vega the visual and photographic magnitudes are the same. If now we measure the photographic magnitudes of the stars, we shall find, for example, that of two stars of the same visual brightness, such as Antares (a red star) and Spica (a blue star), the former will be much fainter photographically than the latter by about two magnitudes. The difference between the numbers signifying the visual and photographic magnitudes of a star is called the *colour-index,* and this, as the name implies, is regarded as a measure of a star's colour. Now the colour of a hot body is an indication of the temperature to which it is raised. A piece of iron in a blacksmith's forge is first dull red in colour, and as the temperature is increased it becomes "white-hot." The surfaces of the stars from which are poured out such amazing quantities of light and heat are similarly at widely diverse temperatures, the blue stars much hotter than the white stars, the latter much hotter than the red stars.

We are now in a position to inquire into the reasons why some stars are very much more luminous than others, why, in fact, some are giants and others are dwarfs. One reason is found in the wide range of stellar temperatures, for the hotter the star the more luminous it will appear, just as the intense glare of the smelting-furnace is hundreds of times more dazzling than the pleasant glow of the domestic fire. The second reason depends on the relative sizes of the stars. Like the sun, the stars are vast gaseous globes, and so far we have no indication as to whether any particular star is of greater or less dimensions than the sun. Let us consider the sun and Capella (or rather the bright component of this star, for it is a double star). As the absolute magnitudes are known, it can be calculated that this star is almost 130 times more luminous than the sun. The quality of the star's light is practically identical with that of sunlight. The star's greater luminosity must then be due to the greater surface of the star as compared with the surface of the sun, just as the amount of illumination which we get from the moon depends chiefly on the area of the lunar surface reflecting light in our direction. When all the pertinent factors are taken into consideration, it is found that this star must have a diameter about 13¾ times the sun's diameter. We know that the solar diameter is 865,000 miles from which it is easily calculated that the star's diameter is almost 12,000,000 miles. The star is undoubtedly a giant as regards dimensions as well as regards luminosity. When we consider red stars, the diversity in size between the giants and the dwarfs is even more amazing; at one extreme, there is the giant Antares with a diameter 450 times that of the sun; at the other extreme are a host of intrinsically faint stars with diameters not much more than a fifth or sixth of the sun's diameter.

We consider now a further characteristic of the stars—namely, Mass. The mass of a star is the quantity of matter of which the star is composed. In the case of our nearest star, the sun, it is found from considerations outside the scope of this book that the sun's mass is about 330,000 times the mass of the earth. The mass of the earth can be estimated in various ways as so many tons. When the calculation is completed, the mass of the sun is found to be two thousand million million million million tons. It may occur to the reader that this answer may only be interesting to those whose delight it is to dabble with stupendous numbers which by very reason of their vastness can have little chance of being comprehended by the human mind. But it will be seen later that this number is of great significance in one of the most interesting problems in the whole realm of astronomical science. The measurement of the mass of the sun may appear to be a problem of very great difficulty; how is it then possible to measure the masses of stars which are at such remote distances from us? We have had occasion to refer to "double-stars"—stars which appear close together in the telescope. At the beginning of last century Sir William Herschel made an important discovery. From observations spread over several years, he showed that in several instances one member of a double star appeared to revolve around the other. His discovery may be conveniently illustrated by means of Fig. 2 relating to the double star Zeta Herculis. This double consists of a brighter star (of apparent magnitude 3·0) yellow in colour and a fainter star $3\frac{1}{2}$ magnitudes fainter and red in colour. Observations of this double show that the fainter star

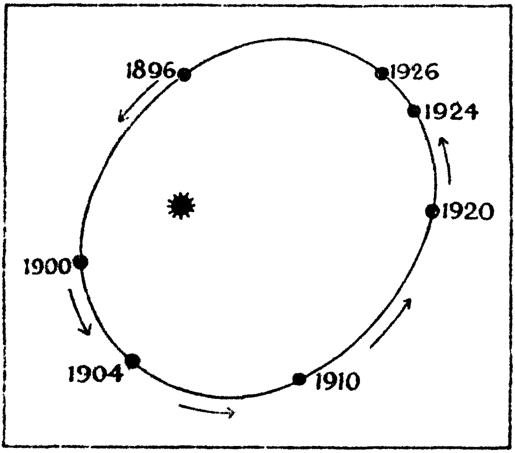

FIG. 2.

(called the companion) revolves around the principal star in a period of thirty-five years. In the solar system orbital motion is familiar; the planets revolve around the sun, the moon around the earth, the satellites around their respective planets. As in the solar system the orbital motion of a planet is controlled by the mutual gravitational attraction of the sun and the planet, so it is inferred that a similar influence operates in the case of the double star of Figure 2. Now the mutual attraction of the sun and a planet depends partly on the masses of the two bodies, and so it is with regard to the double star. From the detailed observations of the double star orbit, it is possible, when the distance of the system is known, to calculate the sum of the masses of the two stars expressed in terms of the sun's mass as unit. Under certain circumtances we can go a step further and calculate the individual masses. In this way it is found that the mass of the principal star of Zeta Herculis is 1·1 times the solar mass, and that the mass of the fainter star is just one-half of the sun's mass. When all the available information, so laboriously acquired, concerning stellar masses is examined, a significant fact emerges: the masses of the stars are all very much alike. The most massive star known has a mass at least 80 times the mass of the sun; the least massive star has a mass just about one-fifth of the solar mass. This relatively restricted range of stellar masses is all the more surprising when we remember the amazing diversity in stellar luminosities; a very luminous star (which we may compare to a powerful searchlight) may be a hundred million times more luminous than an intrinsically faint star (which we may compare to the feeble light of a glow-worm) but the corresponding range in masses is the comparatively limited one indicated by the figures just stated.

The last characteristic which we shall consider here is the average density of the stellar material, density being defined as the amount of matter in a unit of volume—*e.g.*, a cubic foot. From the known dimensions and mass of the sun, we find that the average density of the solar material is about 1½ times the density of water. In stars known as "white dwarfs," the average density rises to the amazing figure of 50,000 times the density of water; a ton of the material of such a star would occupy a volume little more than that of a match-box. At the other extreme are the giant red stars such as Betelgeuse and Antares in which the stellar material is hundreds of times more diffuse than the air we breathe.

CHAPTER II

THE LIGHT OF THE STARS

EVERYONE is familiar with the beautiful succession of colours in the rainbow—red, orange, yellow, green, blue, indigo, and violet. The rainbow is indeed nature's fascinating experiment to show the composite character of sunlight or white light. Two and a half centuries ago Sir Isaac Newton made the first direct contribution to the study of the characteristics of sunlight. Admitting the sun's rays into a darkened room through a small hole in the window screen and allowing the rays to fall on the side of a glass prism, he obtained the familiar rainbow colours. Moreover, he reversed the process and by a means of a second prism combined the different colours to form again white light. The function of a glass prism is very simple; a ray of light falling on a side of the prism in a certain direction emerges from the glass in a somewhat different direction; the prism, in fact, deflects the light by amounts which can be calculated according to the laws of optics. Newton's experiment showed that red light is deflected less than orange, orange than yellow, and so on. Such was the modest beginning in the analysis of the composite light emitted by our nearest star, the sun.

The instrument which has been developed to study in greater detail the characteristics of light is called the *spectroscope*. Suppose we wish to examine the light from an electric lamp. Let us, then, follow the course of the light in its passage through the spectroscope. The light first passes through a very narrow rectangular slit. It is then a diverging beam. The rays are rendered parallel by a lens placed at a distance from the slit equal to the focal length of the lens. The parallel rays now fall on the face of a glass prism and are deflected in their passage through the prism by amounts depending on the colour characteristics of the constituents of the electric light. The light is thus spread out into a ribbon, called a *spectrum*, of the various rainbow colours, red at one end and violet at the other. A small telescope completes the equipment; with it the spectrum can be examined visually in greater detail, or photographed on a sensitive plate placed at the eye-end of this telescope. Such a spectrum, consisting of the succession of rainbow colours, is known as a *continuous spectrum*, but it must not be inferred that every light, whether of terrestrial or celestial origin, produces a spectrum of exactly this nature.

At the beginning of last century, Wollaston made a discovery of very great importance. Examining the spectrum of sunlight he noticed several dark lines at right angles to the direction in which the different spectrum colours were distributed. Some years later, Fraunhofer, with improved apparatus, detected several hundreds more, to the more prominent of which he assigned letters; for example, two prominent lines in the violet part of the spectrum, which are now known to be due to the presence of calcium in the sun, were designated by the letters H and K, a nomenclature which is still in general use to this day. Such dark lines are called *absorption lines.* The solar spectrum is thus not a purely continuous spectrum; owing to the absorption lines, thousands of which have now been detected, it is known as an *absorption spectrum.* The spectra of the vast majority of the stars are of this kind. Fig. 3 gives a picture of the more prominent dark lines in the solar spectrum on the coloured background of the continuous spectrum. In the figure, "red," "orange," etc., indicate the various colour regions of the spectrum.

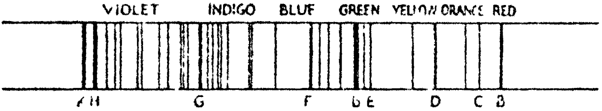

Fig. 3.

What is the interpretation of the dark lines in the solar spectrum? It was not until 1859 that physical science could supply an answer. In that year, Kirchhoff announced the principles governing the production of spectra. Let us consider the simple laboratory experiments which give the necessary clues. Suppose that a few grains of common salt (which is a chemical compound of the metal sodium and the gas chlorine) are held in the flame of a spirit-lamp. Such a flame is almost non-luminous, but as soon as the salt is introduced it is coloured a brilliant yellow. Other chemical compounds of sodium give a similar result. The heat of the flame is sufficient to break up the chemical compound into its constituent elements and to volatilise the sodium. The brilliant yellow colour is thus due to glowing sodium vapour. When this light is examined in the spectroscope, the spectrum is seen to consist simply of two brilliant yellow lines close together. The rather moderate heat of the flame is sufficient to render luminescent only a very few elements. In the laboratory more powerful sources of heat, such as the electric arc and the electric spark are employed. When iron is volatilised in the electric arc, its spectrum is seen to consist of hundreds of bright lines of all colours. To obtain the spectrum of a gas, the vacuum tube is used. This tube contains the gas, with which the experiment is to be made, at low pressure; an electric discharge is passed through the tube which renders the gas luminous; the spectrum is again found to consist of bright lines, the number and colour of which depend on the particular gas concerned. Such spectra are called *bright line* spectra or *emission* spectra. Now let us suppose that a block of lime is heated to luminescence; the temperature at which this occurs is very much higher than the temperature of the flame of the spirit-lamp. The spectrum of the light emitted by the incandescent lime proves to be a continuous spectrum showing beautifully the complete range of colours from red to violet. Now let us interpose the spirit-lamp with sodium chloride in its flame between the glowing lime and the slit of the spectroscope. The spectrum is now found to consist of the brilliant continuous spectrum crossed by two dark lines in the exact positions occupied by the two bright lines due to the glowing sodium vapour in the first experiment. On the results of such experiments, Kirchhoff was led to the following generalisations which are the foundations upon which the vast structure of astrophysics has been reared:

1. A gas under low pressure or the glowing vapour of an element gives rise to a bright-line spectrum, the

number and arrangement of the lines depending on the particular chemical element concerned.

2. When the light of a source giving rise to a continuous spectrum is passed through a glowing gas or vapour whose temperature is lower than that of the source, the cooler gas or vapour absorbs part of the light emitted by the hotter source precisely in those positions of the spectrum at which its own characteristic bright lines appear.

Let us consider the application of these principles to the interpretation of the solar spectrum. This spectrum, as has been stated already, is an absorption spectrum; that is to say, it consists of the succession of rainbow colours forming a continuous spectrum but interrupted by a great number of dark (or absorption) lines. The existence of the absorption lines indicates the presence of gases and vapours at temperatures lower than that of the source producing the continuous spectrum. These gases and vapours, it is inferred, form a kind of atmosphere cooler and less dense than the layers from which are poured out the streams of light which the spectroscope resolves into the continuous spectrum. The radiating surface of the sun is known as the *photosphere;* above it lies the solar atmosphere. The lower levels of the solar atmosphere merging gradually into the photosphere are known as the *reversing layer,* so called because in this region are the vapours of many of the terrestrial elements which at definite positions of the spectrum " reverse " the bright continuous spectrum, producing the dark absorption lines. Above the reversing layer is the much more extensive but tenuous *chromosphere,* rising to a height of several thousand miles above the photosphere. Above the chromosphere and extending to vast heights lies the corona, a very tenuous, gaseous envelope visible only during a total eclipse of the sun. Such, in brief, are the divisions of the atmospheric surroundings of the sun.

But the dark absorption lines tell us more. They provide the clues by which we can investigate the chemical constitution of the solar atmosphere. We have seen that sodium in the flame of a spirit-lamp gives rise to two bright yellow lines close together. If in the solar spectrum there are two dark absorption lines occupying the identical positions in the yellow region, it may be inferred from the second of Kirchhoff's principles that sodium is present in the solar atmosphere. The vapour of iron rendered luminous in the electric arc produces a spectrum consisting of hundreds of bright lines; these lines can be matched one by one with the dark lines in the solar spectrum, showing that iron is a constituent of the sun's reversing layer. In this way it is found that some fifty of the chemical elements found on the earth exist also in the sun. The case of helium is worthy of more detailed notice. In 1868, Sir Norman Lockyer observed a prominent yellow line near the position of the double yellow line due to sodium while examining in his spectroscope the solar prominences, which are immense gaseous eruptions sometimes extending several hundred thousand miles above the photosphere. No known terrestrial element produced a line in this particular position, and from the circumstances it was inferred that the solar atmosphere contained a new gas, which was named helium. In 1896, Sir William Ramsay recognised this gas as a constituent or product of the rare mineral uranite. More recently, helium has been found in considerable quantities in the natural gases which bubble up in certain wells, notably in Texas. Helium proved to be the second lightest gas known, just four times heavier than hydrogen, the lightest gas of all. We are familiar with the use of hydrogen in the giant airship, but owing to its inflammable nature the employment of hydrogen for this purpose exposes the craft to very serious dangers, as was abundantly proved in the Great War. Helium is not open to this objection.

Although the lifting capacity of helium is but a quarter that of hydrogen, vast quantities of the gas had been accumulated towards the end of 1918 for use in the aircraft of the Allies; such aircraft would have been immune from the fatal effects of the explosive bullet so destructive against the hydrogen-filled aircraft.

Let us now consider the nature of light. When a pebble is thrown into a still pond, a succession of waves travel outwards on the surface of the water. It is a simple matter to measure the distance between successive wave-crests (this distance is called the *wave-length*) and the speed with which the waves are propagated outward (this is the wave-velocity). We can also observe the number of waves which pass a particular spot in a second (this number is known as the wave-frequency or simply the *frequency*), and it is evident that the frequency is related simply to the wave-length and the wave-velocity. According to the theory of light propagation, known as the wave-theory, light is conceived to travel in waves through the hypothetical medium called the ether with a velocity of 186,000 miles per second, and this velocity is the same for all wave-lengths of light. The difference between what we call red light and blue light is due to the difference between the wave-lengths of red and blue light and is manifested by the different physiological reactions of the eye with its associated organs to light of such varying wave-length characteristics. In the rainbow or in the continuous spectrum there is a gradual change from one colour to another; in terms of wave-length we can interpret this as a progressive change in wave-length from one end of the spectrum towards the other. Light of one particular wave-length is called monochromatic light, and we thus conceive the continuous spectrum to be made up of a very large number of monochromatic radiations, each with its own distinctive wave-length. We have seen that the solar spectrum is crossed by numerous dark absorption lines occupying definite positions in the spectrum and therefore associated with definite wave-lengths. If, for example, iron vapour were not present in the solar atmosphere, there would be no sign of the so-called iron absorption lines, and the light radiated from the photosphere of the corresponding wave-lengths would make its due contribution to the continuous spectrum. Iron vapour, under the conditions in which it exists in the solar atmosphere, has thus the property of absorbing light of particular wave-lengths from the continuous radiation of the photosphere, and by Kirchhoff's principles these wave-lengths are precisely the same as those of the bright lines observed when iron is rendered luminous in the electric arc.

The wave-lengths of the bright lines produced by glowing gases and vapours can be measured with great precision by laboratory methods, on the details of which we have not space to dwell. The wave-lengths turn out to be exceedingly small. If an inch is divided into 43,000 equal parts, each part is just about equal to the wave-length of the yellow lines of sodium. The ordinary units of length are evidently unsuitable so far as the wave-lengths of light are concerned. The unit adopted in spectroscopy is the Angstrom unit, which is defined to be the ten-thousand-millionth part of a metre. (The metre is a scientific unit of length equal to a little more than 39 inches.) For example, the wave-lengths of the two yellow sodium lines are denoted thus: 5898 A and 5890 A, the letter A referring to the Angstrom unit. It is found that the wave-lengths of the light forming the visible spectrum range approximately between 3000 A at the violet end of the spectrum to 7500 A in the red. The adjective "visible" has been used purposely, for it is only to light or radiation of wave-lengths within the limits just quoted that the eye is sensitive. Outside the violet end lies the region called the ultra-violet; to ultra-violet radiation the ordinary photographic plate is most sensitive. The X-rays familiar in medical practice are radiations of but a few Angstrom units in wave-length. Beyond the red end of the visible spectrum is the region known as the infra-red, the region of heat radiations. Beyond that are the wave-lengths of electro-magnetic manifestations, the longest of which, measured in yards or metres, are familiar in wireless telegraphy. In practical astrophysics, we are concerned only with the radiations giving rise to the continuous spectrum and its extensions in the ultra-violet and infra-red.

A brief reference must be made to the method of measuring the wave-lengths of the dark lines—for example, in the solar spectrum—and identifying them with the characteristic lines produced in the laboratory by the terrestrial elements. We shall first suppose that the sunlight is allowed to pass through the upper part of the spectroscope's slit and, after being spread out into a spectrum, records its features on a sensitive photographic plate. With suitable apparatus the light from glowing iron vapour, for example, can be made to pass through the lower half of the slit, and the hundreds of bright lines due to iron will leave their impression on the plate in a strip just below the strip forming the solar spectrum. The iron lines, whose wave-lengths are accurately known, serve as a kind of scale, by means of which the wave-lengths of all the lines in the solar spectrum can be measured. The iron spectrum, in this case, is called a *comparison spectrum*. The presence of aluminium, for example, in the solar atmosphere is then deduced from a comparison of the series of lines in the laboratory spectrum of aluminium with lines of the same wave-lengths in the solar spectrum.

It may have appeared to the reader that the hypothesis of a solar atmosphere responsible for the appearance of the absorption lines in the sun's spectrum is a somewhat bold inference from the generalisations of

Kirchhoff, and he may naturally inquire for additional proofs. It must first be remarked that there can be no doubt concerning the high temperatures at which the gases and vapours must exist in the sun's atmosphere (if such there be). The gases and vapours must, in fact, be glowing and behaving in much the same way as the sodium vapour in the flame of the spirit-lamp. It follows that, if our hypothesis is correct, the solar atmosphere ought to give a bright line spectrum when shielded from the influence of the more intense radiation of the photosphere, just as the sodium vapour in the flame produces by itself a bright line spectrum. The circumstances of a total eclipse of the sun provide the desired conditions. At the instant of the beginning of totality, the dark body of the moon has just covered the last visible crescent of the photosphere, leaving exposed, so to speak, for a moment or two the narrow girdle of solar atmosphere. When observations are made visually with a spectroscope, the slit being arranged tangentially to the fast diminishing crescent of the sun, the spectrum seen is of course the ordinary solar spectrum consisting of the beautiful continuous spectrum crossed by a multitude of dark lines. But at the moment when totality commences there is a sudden and beautiful change; the continuous spectrum vanishes, and bright lines of varying hues flash out in the positions occupied just a moment before by the dark absorption lines. This spectrum is known as the flash spectrum, and is evidently the manifestation of a shell of glowing gases and vapours to which we have already given the name of the solar atmosphere. A photograph of the flash spectrum provides definite information concerning the heights to which the various gases and vapours extend above the photosphere. It is remarkable that the vapours of the comparatively heavy element calcium reach a height of at least 5,000 miles, higher even than hydrogen.

So far we have confined our attention mainly to the sun, because its spectrum can be studied much more thoroughly than the spectra of even the brightest stars. With the giant telescopes, the spectra of stars as faint as the tenth magnitude can be adequately photographed. Like the solar spectrum, the spectra of the vast majority of the stars are absorption spectra, but there is an immense variation in the number and source of the absorption lines crossing the continuous spectrum and in the characteristics of the continuous spectrum itself. According to the nature of their spectra, the stars are arranged in spectral classes, the principal features of which will now be briefly described.

The spectral classes are denoted according to what is known as the Draper classification by the letters O, B, A, F, G, K, M, R, N, S. The spectra of one particular class are further sub-divided; for example, the sub-divisions of Class A are denoted by A 0, A 1, A 2 . . . A 9, a nomenclature which indicates a gradual progression in spectrum characteristics within the more comprehensive Class A. We shall consider here only the main sequence comprised within the Classes B to M, to which the vast majority of stellar spectra belong.

Class B.—The number of absorption lines is comparatively small; these are mainly due to helium and hydrogen. Stars of this class are bluish in colour.

Class A.—The hydrogen lines are exceedingly prominent. Helium lines are absent. There are faint lines due to several metallic elements, notably iron, calcium, and titanium. Stars in this class are bluish-white in colour.

Class F.—The hydrogen lines are much fainter than in the preceding class. The metallic lines are more conspicuous. Stars of this class are white in colour.

Class G.—Stars in this class have spectra very similar to the solar spectrum. The lines due to metals are prominent. Stars in this class are yellow in colour.

Class K.—In this class, absorption bands, which are due to glowing compounds—such as titanium oxide—make their appearance. Calcium lines are conspicuous. Stars in this class are orange in colour.

Class M.—The absorption bands of compounds form the most conspicuous feature of the spectra of this class. Stars of this class are red in colour.

This is a very abbreviated account of the classification of stellar spectra, and it must be understood that there are other important features, to some of which reference will later be made. Meanwhile we shall make a few general remarks. In Chapter I. we considered colour as constituting a definite characteristic of the stars, and we suggested that colour is a qualitative indication of the surface temperatures of the stars—blue stars being hotter than white stars, and so on, until we reach the red stars, which are the coolest of all. Referring to the classification according to spectra, the reader will notice that the sequence B to M is a sequence of decreasing surface temperature. Let us consider the red M stars. In their spectra are to be found the absorption bands due to certain chemical componds. We have seen that only the moderate heat of a spirit-lamp flame is sufficient to break up the chemical compound sodium chloride (common salt) into its constituent elements, sodium and chlorine. At the much greater temperature of the electric arc most chemical compounds are dissociated in a similar way. Titanium oxide, however, proves obdurate in this respect until a somewhat higher temperature is reached. In the atmospheres of the red stars, titanium oxide exists as a compound. We thus obtain a clue to the surface temperature of these stars. From this consideration and others, the surface temperature of the red stars is placed at about 3,000° Centigrade. Consider now the stars of spectral class B. The absorption lines appear to indicate that the atmospheres consist of little else than hydrogen and helium. Is this a correct inference? At the high temperatures prevailing in these stars chemical compounds evidently cannot exist. May it not be that, for a similar reason, the ordinary elements, such as iron, are unable to exist in the atmospheres of these stars in the form with which we are familiar on the earth? These questions lead us to consider the constitution of matter and the behaviour of the elements under the extraordinary physical conditions prevailing in stellar atmospheres.

Chemically, the smallest particle of an element, such as hydrogen or iron, is the atom, and the properties of the several elements depend on the constitution and structure of the atoms of which they are respectively composed. Recent research in physics points unmistakably to the electrical constitution of matter—that is, in the last resort, of atoms. Consider the simplest atom of all, the hydrogen atom. This consists of a *nucleus,* around which revolves a single *electron.* The electron carries a definite charge of negative electricity (which has been measured), and this charge—the unit negative charge—is the same for all electrons. As hydrogen is, electrically, neither positive nor negative, it is inferred that the nucleus of the hydrogen atom carries the unit positive charge of electricity. The nucleus of the hydrogen atom is generally called a *proton.* Just as the revolution of a planet around the sun is explained in terms of the mutual gravitational attraction of the two bodies, so the revolution of the electron around the proton is explained in terms of the mutual electrical attraction of these oppositely charged particles, the proton and the electron. The mass of a proton has been found to be 1,847 times that of an electron; thus the mass of the hydrogen atom is effectively concentrated in the proton or nucleus. The atoms of other elements are more complicated structures, and have been likened to miniature solar systems. Thus, for example, the atom of sodium consists of a nucleus around which revolve 11 electrons, which we may designate the planetary electrons. The nucleus of the sodium atom is itself believed to be a complicated structure consisting of 23 protons and 12 nuclear electrons bound together in a way not yet understood, the size of the whole being but a minute fraction of the dimensions of the orbits described by the planetary electrons. As the sodium atom contains 23 protons and the hydrogen atom but 1, the mass of the sodium atom is effectively 23 times the mass of the hydrogen atom, a result well-known from chemical experiments. These examples may be sufficient to indicate the general lines on which atoms of the elements are built.

Now let us inquire into the processes by which it is believed atoms are able to emit or absorb light; for simplicity, we shall consider hydrogen. When hydrogen is made to glow in a vacuum tube, its spectrum consists of a series of bright lines whose wave-lengths are found to follow a simple mathematical law. The hydrogen atom thus appears to be very discriminating in the kind of light which it emits under the conditions prevailing in the vacuum tube. The electrical discharge in the tube releases a supply of energy, part of which is assimilated by the hydrogen atoms and subsequently released by them in the form of light energy; a parallel example is the heat energy supplied to the sodium atoms in the flame of a spirit-lamp. But what is the result of supplying energy to a hydrogen atom? The atom has but one electron revolving around a single proton, and if energy is pumped into an atom, the electron must be forced out into a bigger orbit against the mutual electrical attraction of nucleus and electron. At first sight it would appear that there are no limits to the number of orbits which the planetary electron may subsequently describe, but with such a state of affairs the particular characteristics of the hydrogen spectrum could not possibly be explained.

In the Bohr theory it is supposed that the electron can revolve around the nucleus only in certain definite orbits which, for simplicity, we shall regard as circles with the nucleus at the centre. If we number these circles, starting from the one nearest the nucleus, 1, 2, 3, 4, etc., then, according to the theory, the radii of these circles are in the proportions 1, 4, 9, 16, etc. In the vacuum tube, the atoms of hydrogen absorb the energy provided by the electric discharge, but only in certain doses, called quanta. If the electrons in the individual atoms are all originally revolving in orbit number 1 (as they are believed to do when the hydrogen is cold), then, by the absorption of energy, the electrons jump to more distant orbits, some to number 2, some to number 3, and so on. But the atoms are no sooner blown out, as it were, to much greater dimensions than they are ready to disgorge all or part of the energy which they have just swallowed. The electron of one atom will jump back from orbit number 6, say, to orbit number 2, another from number 5 to number 3, and so on. The release of energy when the electrons jump back from the orbits number 3, 4, etc., to orbit number 2 takes the form of light radiations with the wave-lengths those of the bright lines in the hydrogen spectrum. There is a mass of evidence supporting Bohr's theory of the atom, strange as the theory may seem.

To get a glimpse of the explanation of absorption lines, let us return to our experiment with the glowing sodium in the flame through which streams the radiation of the hotter luminous lime. The light energy from the lime is of all wave-lengths—the light, in fact, is resolved by the spectroscope into a continuous spectrum. The sodium atom consists, as we have seen, of a nucleus and 11 planetary electrons, but it is the outermost electron only which behaves in the manner, just described, of the single electron of the hydrogen atom. The sodium atoms absorb packets of the more intense radiation from the lime—in the process, the active electron jumps to a more distant orbit. As in the case of the hydrogen atom, the sodium atom is ready to part with its recently acquired energy; the active electron then finds itself in a lower orbit, and the result is the emission of light with a particular wave-length depending on the nature of the electron's jump. Now, this emission may take place in any direction, and so when we consider all the atoms, only a small proportion at any given moment will project the emitted light or radiation in the direction between the flame and the slit of the spectroscope; in other words, only a fraction of the light from the lime, of the wave-lengths characteristic of the sodium atom, passes through the slit. Thus the continuous spectrum seems to be robbed of part of its light at certain wave-lengths, and there we see the dark absorption lines.

There is one other atomic phenomenon, of supreme interests in astrophysics, to which we shall refer. When iron is made to glow in the electric furnace (the temperature is considerably less than in the electric arc), the spectrum consists of certain definite bright lines; if the iron is made luminous by the much more powerful electric spark, a completely different set of lines is observed. In the furnace, the iron atoms have their complete array of planetary electrons, but under the fiercer conditions of the spark, the outermost electron in each atom is torn off, leaving the atom with a net unit charge of positive electricity. The iron atoms in this state are said to be *ionised*, and the spectrum lines which the ionised element produces are generally called *enhanced* lines. Under still more severe conditions, the iron atom may lose a second electron; in this state it is said to be doubly ionised. In spectra of the A class stars, the lines of ionised iron, for example, are well marked, whereas in stars of classes K and M these lines do not appear at all, although the lines due to the normal atom—that is, the complete atom—are visible. Here we have another clue leading us to an understanding of the surface temperatures of the stars. But high temperature is not the only factor controlling the ionisation of the elements. Another factor is the density of the gas or vapour. If the iron vapour is very dense—that is, if there is a very large number of atoms to every unit of volume so that the atoms are tightly packed together—ionisation is not so easy as when the gas density is small; for in a dense gas no sooner is an electron expelled from one atom than it is picked up by another atom, also temporarily deficient, like the first, of an electron. Effectively, the atoms are complete, although the electrons are playing a game of "general post." When the gas or vapour is much less dense, there will always be a certain proportion of atoms in the ionised state, for the capture of a flying electron by an ionised atom will be of less frequent occurrence. Now, if the temperature and gas-density are given, it is possible to calculate the proportion of ionised atoms to normal atoms. In particular, it is possible to discover the relation between temperature and pressure when all the iron atoms are just ionised. Consider now the spectral series B to M. In the spectra of some stars, the lines of both the normal and ionised atoms are visible, but as we examine stars of successive types, we shall come to a point in the spectral sequence where the normal lines have just disappeared; there is then a definite relation between temperature and pressure in the atmospheres of stars of this type. We can consider other elements in a similar way, and from the mass of information so derived it is possible to deduce the temperatures and pressures in the stellar atmospheres.

There are other methods of deriving estimates of stellar temperatures. We mention but one. When the spectrum of a B type star is observed visually, the continuous spectrum is most intense in the blue end of the spectrum—this is the reason, of course, why the star is bluish in colour—and the red end is comparatively faint. In the same way, the continuous spectrum of a red star is most intense in the red end, the blue end being inconspicuous. According to physical laws, the maximum intensity in the spectrum produced by a hot body moves from the red towards the blue as the temperature is raised; and to each wave-length at which a maximum intensity occurs corresponds a definite temperature. The following table gives the average results of several investigators, using different methods, for stars of different spectral class:

Stellar Temperatures.

Spectral Class.	*Temperature.*
Bo	25,000° Centigrade
B5	14,000° ,,
Ao	10,000° ,,
Fo	8,000° ,,
Go	6,000° ,,
Ko	4,000° ,,
Mo	3,000° ,,

Why is it that the spectra of the very hot B type stars show little else than the lines of hydrogen and helium? Must it be inferred that the atmospheres of these stars consist only of the two gases mentioned? At the high temperature of the Bo stars, the helium atoms have one of their two revolving electrons removed owing to the intense radiation; they are therefore singly ionised. The helium atom retains its electron system with greater tenacity than any other element; it is thus very difficult to detach an electron from the atom. One of the many achievements of astrophysics is the measurement of the tenacity with which atoms in the normal state and in the ionised state cling to their electron systems. But in the Bo stars, the disruption of the helium atom is accomplished. It follows that the atoms of such elements as iron and sodium are in a shattered condition—if these are present in the atmospheres—and the characteristic lines of such disrupted atoms do not appear within the wave-length limits of the visible spectrum. Such, on the ionisation theory, is the explanation of the apparent absence of many of the familiar elements in the atmospheres of the hottest stars.

We conclude this chapter by describing an amazing application of the principles discussed in the previous pages. From the study of the spectrum of a star it is now possible to deduce the absolute magnitude (or the luminosity of the star), and as the apparent magnitude is easily measured, the distance of the star can then be found. This is indeed an extraordinary achievement of modern astrophysics. In Chapter I. we referred to the stars of high luminosity, called giants, and the stars of low luminosity, the dwarfs. Consider a giant and dwarf of the same spectral type—that is to say, of the same surface temperature. The greater luminosity of the giant is a consequence of its greater bulk. The density of the gases in its atmosphere will then be very much less than the density in the atmosphere of the dwarfs. The conditions for ionisation are thus more favourable in the giant than in the dwarf, and therefore we should expect to find a line of a particular ionised element more prominent in the giant than in the dwarf, and the reverse for a line produced by the normal atoms. As we proceed from stars of spectral class F to stars of class K, for example, there will be a change in the relative prominence or intensity of such pairs of lines as have been considered. Now, taking a sufficient number of stars of the spectral types concerned, whose distances have been accurately measured by the direct trigonometrical method, and whose luminosities (or absolute magnitudes) are therefore known, we can see how the changes in luminosity are related to the changes in the relative intensities (which can be measured with suitable apparatus) of pairs of lines of the kind considered. Stars of known distance and of known luminosity thus form the foundations of the scheme. To derive the distance of any other star, we have to measure the relative intensity of one or more pairs of selected lines in its spectrum. To these measures corresponds a particular luminosity or absolute magnitude. The apparent magnitude of the star being presumed known, the distance in light-years, or parsecs, is then easily deduced. This remarkable method of deriving stellar distances is many more times more rapid than the fundamental trigonometrical method, and the distances of thousands of stars have already been measured in this way.

CHAPTER III

THE VELOCITIES OF THE STARS

One of the greatest achievements of eighteenth-century astronomy was the discovery that the stars are not "fixed" and motionless. Everyone is familiar with the constellation of Orion, the bright stars of which appear to maintain the same well-known configuration night after night and year after year. But careful telescopic observations, made at intervals of a few years only, reveal minute changes in the relative positions of the stars in the sky. Such changes are best measured by means of photographs taken at intervals, say, of twenty years. Suppose we are at some distance from a road along which a man is walking. At the end of a minute the direction in which we see him has slightly altered, and if we had some simple apparatus we could easily measure this change in direction as so many degrees per minute. It is by an analogous method that astronomers are enabled to measure the very minute changes in the configurations of the stars. The information so derived is extremely valuable; if we know the distance of a star and the rate at which its position is changing in the sky relatively to the background of stars we can deduce its speed at right angles to the line of sight. It is found in this way that the stars are moving with amazing speeds; perhaps 10 miles per second is not far away from the average speed of the stars. But in our illustration observation shows more than change of direction; in addition, we notice that the man's distance from us is increasing (or decreasing), and here again it would be comparatively simple to find out the rate (for example, in yards per minute) at which the man's distance from us is increasing or decreasing at any particular time. Spectroscopic observations enable us to measure the velocities with which the stars are approaching us or receding from us; these velocities are known as line-of-sight or *radial velocities*.

We explain now the principle underlying the spectroscopic method of measuring the radial velocities of the stars. Consider the waves on the surface of the sea. The wave-crests are travelling in a certain direction with a certain speed. If we imagine ourselves to be in a boat at anchor, we can count the number of wave-crests passing the boat in any convenient unit of time, say a minute. If we know the wave-velocity—that is, the speed at which the waves are travelling—we can evidently find out by a simple calculation the distance between any two successive wave-crests—that is to say, the wave-length. If now our boat is moving in the direction opposite to that in which the waves are being propagated, we shall clearly meet more waves per minute than passed the anchored boat in the same interval of time, and so the wave-lengths will appear shorter. So it is with light-waves. Suppose a star is approaching us, or, stated differently, suppose we are moving towards a star. The star is sending out light of different wave-lengths, but let us only consider one element of the composite light characterised by a particular wave-length. Owing to the velocity of approach, this wave-length will appear to be shorter than it would be if the distance between us and the star were constant. With the spectroscope we can measure such a change in wave-length. The light from the star is admitted through the top half of the slit of the instrument and the spectrum is photographed on a sensitive plate; light from glowing iron vapour, for example, is then allowed to pass through the bottom half, giving a comparison spectrum consisting of lines of known wave-length (see page 26). Fig. 4 represents diagrammatically the stellar spectrum, which we suppose to contain iron lines, and the comparison spectrum, showing the stellar lines displaced a little towards the violet end with reference to the corresponding iron lines in the comparison spectrum. (*The lines in the* stellar spectrum are absorption lines, whereas the lines due to the glowing iron vapour are bright lines; for simplicity we do not make this distinction in the diagram.) The actual amount of the displacement of any one line in the star's spectrum depends on the

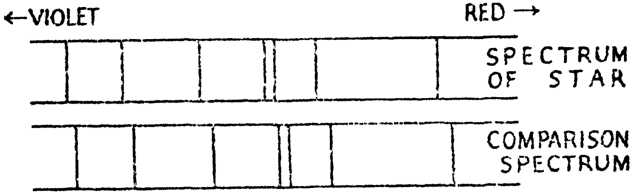

FIG. 4.

ratio of the velocity of approach to the velocity of light. The latter velocity is known to be 186,000 miles per second; consequently from the measured displacement we are enabled to calculate the velocity with which the star is approaching us. If the star is receding from us then a similar argument shows that the stellar lines will be displaced towards the red end of the spectrum with reference to the corresponding lines in the comparison spectrum. If the stellar spectrum contains hydrogen lines, for example, the wave-lengths are measured and the displacements due to the star's velocity of approach or of recession are inferred from the comparison with the laboratory wave-lengths. In this way the radial velocities of several thousands of stars have been measured. It is to be remarked that the spectroscope furnishes directly the stellar radial velocity expressed as so many miles per second, without any reference to the star's distance from us.

There is one consideration, however, that calls for some attention before we proceed further with our discussion of radial velocities. Our instruments are set up on the surface of the earth which is a more or less spherical body spinning about an axis in the period of a day and revolving about the sun in the period of a year. The telescope has thus a continually varying velocity in space and therefore our observations of the radial velocity of a star must include an effect depending on the circumstances already mentioned. We need not delay over the effect produced by the velocity of the telescope due to its being whirled round in the course of a day for this effect can be avoided altogether by making the observations at suitable times. We know that the earth describes an almost circular orbit around the sun of radius nearly 93,000,000 miles with an average speed of about 18½ miles per second. Let us consider a star whose direction lies in the plane of the earth's orbit—known as the plane of the ecliptic. For simplicity we shall suppose that the distance between the sun and the star remains constant. When the earth is at the point A of its orbit (Fig. 5) it is moving towards the star with a speed of 18½ miles per second. If the star's spectrum is photographed on this date it will show an apparent velocity of approach of 18½ miles per second. Six months later the earth will be at the point B of its orbit, its direction of motion being now opposite to the direction of the star. The spectrum of the star photographed on this date will thus indicate a velocity of recession amounting to 18½ miles per second. If the star is actually receding from the sun, say with a velocity of 50 miles per second, then observations made when the earth is at A will indicate a velocity of recession of 50 *minus* 18½ or 31½ miles per second, while six months later, when the earth is at B in its orbit, the observed radial velocity will be 50 *plus* 18½ or 68½ miles per second. It is not difficult to see that, whatever the star ob-

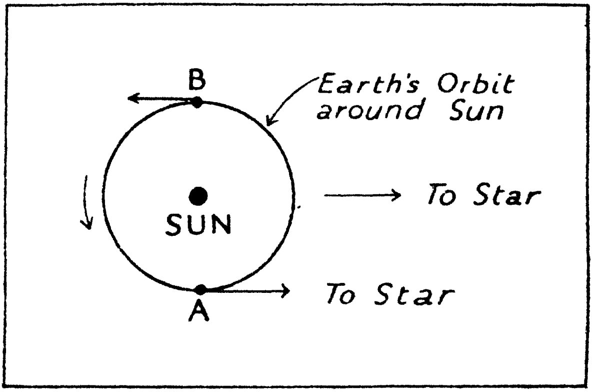

FIG. 5.

served and whatever the circumstances under which the observations are made, the effect of the earth's orbital velocity can be eliminated completely and we finally obtain the star's velocity of approach to the sun or its recession from the sun as the case may be. This is the sense in which the term "radial velocity" as applied to the stars is to be understood.

The principle which we illustrated in Fig. 5 has an application to a practical problem which has engaged the attention of astronomers for centuries—namely, the measurement of the distance of the earth from the sun. It seems almost incredible that this fundamental astronomical distance, the measurement of which in the past has involved such laborious and lengthy observations, should appear as a by-product in astrophysical observations of the spectra of stars. Let us return to Fig. 5. Whatever the velocity of the star, the spectra obtained when the earth is at A and when it is at B will show a relative displacement of the spectrum lines which, interpreted in terms of radial velocity, will be equivalent to twice the earth's orbital velocity. By making numerous observations of several stars it is evidently possible to measure the earth's orbital velocity with high accuracy; it is, of course, expressed as so many miles per second. We know the number of seconds in a year, and thus we can calculate easily the circumference of the circle representing the earth's orbit. It is then but a step to derive the radius of the circle—that is to say, the earth's distance from the sun. Actually the earth's orbit is an ellipse, approximating closely, however, to a circle, but the necessary refinements in calculation are easily taken into account. The results obtained by the spectroscopic method compare, as regards accuracy, very favourably with the results derived by the older methods.

The radial velocities of the stars are generally a few miles per second. But there are exceptional stars with extraordinarily high velocities. In a catalogue of the radial velocities of nearly 4,000 stars, published at the beginning of 1928, the following information is given of the greatest measured velocities of approach and of recession of stars of the various spectral classes.

Greatest Radial Velocity.

Class.	*Approach.* (*Miles per Second.*)	*Recession.* (*Miles per Second.*)
B	37	63
A	217	210
F	202	140
G	150	191
K	100	170
M	119	177

The conception of the system of stars all in ceaseless movement leads naturally to the idea that the sun itself with its family of planets is in motion in space. An aviator may gauge his speed and direction by observation of the familiar landmarks below, but the astronomer has no fixed marks in space to which he may refer when attempting to measure the solar motion. The stars are like ships sailing aimlessly about on a vast uncharted sea. If we imagine ourselves on board a particular ship proceeding on a certain course, the distance between our ship and those ahead will on the whole be lessening, whereas the distance from those astern will be on the whole increasing. We may, then, if we like, refer the speed of our ship, and the direction in which it is proceeding, to the ships ahead and astern; we may go a step further and consider the ship's motion with reference to all the ships within sight. It is in some such way that we think of the sun's motion with reference to the stars. We have already referred to the minute changes in the positions of the stars in the sky. Almost a century and a half ago Sir William Herschel used all the available information of this kind to determine the direction in which the sun is moving with reference to the stars. The measures of radial velocity enable us to obtain this direction independently and also the speed of the sun with reference to the stars. All investigations of the solar motion fix the direction within a few degrees of the direction in which we see the bright star Vega—this direction is known as the *solar apex.* Let us now see how the solar speed is measured. Radial velocity measures of as many stars as are available for observation in the vicinity of the solar apex will indicate on the average a particular velocity of approach which we may either interpret as the velocity of approach of this group of stars towards the sun or a velocity of approach of the sun towards the group, as in our illustration of the ships. In the same way the stars in that part of the sky (known as the ant-apex) opposite to the solar apex will on the average indicate a velocity of recession. If the stars are roaming space with haphazard speeds and in haphazard directions, the average velocity of recession and of approach which we are considering ought to be equal, and either ought to be a measure of the solar motion. In practice, astronomers do not limit themselves to the comparatively few stars near the solar apex or near the ant-apex, but make use of as many stars as come within reach of their instruments, whatever the positions of the stars in the sky may be. The results of many investigations agree in fixing the solar velocity at 12 miles per second. Compared with terrestrial standards, this is a stupendous speed. In the Schneider Cup race the winning aeroplane attained a speed of about 300 miles per hour, or one-twelfth of a mile per second; the solar speed is thus 144 times the greatest speed yet attained on the earth. In the universe there are bodies moving with yet more immense speeds; the greatest radial velocity so far measured is about 1,100 miles per second.

Great as the speeds of the stars are, vast intervals of time are required to elapse before they cover even a distance equal to that between the sun and the nearest star. When we express stellar distances in terms of light-years, we do obtain some kind of impression of the vastness of interstellar space. The following example may help to strengthen this impression. The sun, as we have seen, is travelling almost in the direction of Vega with a speed of 12 miles per second. Vega is one of our nearest stellar neighbours, just thirty-four light-years away. To travel over this distance, the sun would require 500,000 years and the fastest aeroplane about seventy million years. It is evident that the chance of celestial collisions is exceedingly small indeed.

We mention in a word or two a curious result which emerges from the study of radial velocities from which the effects of the solar motion have been removed. It is found that the average velocity of stars of spectral class B is about 5 miles per second, and that the average for the other spectral types increases as we pass along the spectral sequence B A F G K M to about 10 or 12 miles per second for stars of class M.

On page 16 we referred to double-star systems, in which the fainter components appear to revolve around the brighter stars. In most of these double stars the components are separated by distances generally ten times at least the distance of the earth from the sun. If a double star consisted of two components a few million miles apart, the most powerful telescope in the world would be unable to reveal the system as a pair of stars. Again if we imagine any well-known double star removed to a distance several times further from us the components would then appear much closer in the telescope, and at still greater distances the system would simply appear as a single star. The detection of a visual double star then depends on two factors; the components must be separated by distances comparable with the distances of planets like Saturn and Uranus from the sun, and also they must, as stellar distances are counted, be comparatively near us. Alpha Centauri, one of the brightest stars in the southern sky and the nearest of all, is in reality a double star easily visible as such in a small telescope; its components are at an average distance apart some twenty-three times the distance between the earth and the sun. If, however, it were several hundred times further off, it would appear in the telescope as a rather faint star without any suspicion of its double character. The spectroscope overcomes many of the disadvantages of visual observations so far as the detection of binary systems is concerned; in fact, the nearer the two components actually are (in miles) the greater generally is the chance of discovery of duplicity. Double stars discovered by means of spectroscopic observations are known as *spectroscopic binaries*. Let us see how the spectroscope achieves such discoveries and what is to be learnt from them.

Suppose we are watching an athlete running at a uniform speed round a circular track some distance away from us. At one point in the track his direction of motion is directly towards us; in astronomical language his velocity of approach is greatest at that moment. Some time later he will be running for a moment exactly at right angles to the direction in which we view him, and for a moment or two the distance between us and the runner will be hardly altering; his radial velocity is then zero. Some time later he will be running directly away from us, and the radial velocity of recession will then be greatest. And so on round the track. The point of the illustration is that the radial velocity will be gradually fluctuating between two definite limits, one the maximum velocity of approach, the other the maximum velocity of recession, and the observed changes will be repeated in every lap run. Consider now a double star. Each component will describe an orbit around the common centre of gravity. If we fix our attention on one component we shall find that its radial velocity will follow the same kind of changes as in the case of the runner, and the period within which these changes occur is the period of revolution of the binary. If we photograph the spectrum at intervals during a period the lines of the spectrum will fluctuate as regards position in a definite manner, indicating now a velocity of approach and now a velocity of recession. Now, as each component is revolving around the common centre of gravity, it follows that when one is approaching the other is receding, and *vice versa*. If the two components are sufficiently bright to record their lines on the photographic plate the lines, say of hydrogen, will generally appear double (we will assume that hydrogen lines are common to both stars). Twice during a period the lines will coalesce and appear single; this will occur when both components are moving in their respective orbits at right angles to the line of sight. Moreover, if we suppose that a hydrogen line in one component is more conspicuous than the corresponding line in the other component, a series of photographs will show the conspicuous line sometimes on one side of the less prominent line and sometimes on the other. Such are the changes to be anticipated in the spectrum lines of a spectroscopic binary. In 1889 the late Professor E. C. Pickering made the first discovery of this kind. The bright star Mizar in the Great Bear is itself a visual binary. A series of spectra of the brighter component showed the characteristic doublings of the spectrum lines which we have just described. The bright component of Mizar is thus itself a double star. When both components of a spectroscopic binary are sufficiently bright to be photographed spectroscopically, a detailed study of the cyclical changes in the lines leads to one definite piece of information—namely, the ratio of the masses of the components. We can also determine the least mass which can be assigned to each component (it is impossible to determine from observations the angle at which the orbital plane of the binary is inclined to the line of sight; and this angle of inclination, whatever its value may be, is inextricably mixed up mathematically with the value of the mass of each component). However, when we consider a large number of spectroscopic binaries of the same spectral class, we can adopt an average value for the factor depending on the inclination and so derive reliable estimates of the stellar masses. In this way it is found that stars of class B0 to B2 are about ten times more massive than the sun, with a diminution in mass for succeeding spectral types. The most massive star known is a spectroscopic binary, whose components have masses at least seventy-five and sixty-three times the mass of the sun.

In the majority of spectroscopic binaries one component is considerably brighter than the other; the result is that only one set of fluctuating lines is visible in the spectrum for the fainter component is comparatively so feeble that its characteristic lines are not registered on the photographic plate. Such binaries do not provide much information of value.

More than half of the spectroscopic binaries hitherto observed have periods less than ten days. When the periods are very short the components must be almost in contact. Such a state of affairs naturally suggests the question "How do such systems come into being?" Astronomers generally believe that spectroscopic binaries are the result of the breaking up of single stars owing to rotation. It is hardly possible here to go into the details of the suggested explanation. Perhaps it may be sufficient to give a hint of the process. As a star grows older it contracts. If at an early stage in its history it acquired a rotation, then as time goes on this rotation increases. Under certain conditions this rotation may become so great as to jeopardise the stability of the star and it seeks security by dividing into two. Such is believed to be the process resulting in the birth of the close spectroscopic binary.

CHAPTER IV

VARIABLE STARS

By a variable star we mean one whose light appears to us to fluctuate in brightness. Such light changes may be periodic in character, the cycle of changes being constantly repeated, just as the seasonal changes on the earth are repeated year after year. We distinguish two classes of periodic variable stars. In one class, the period is constant and the characteristics of the light-changes are exactly repeated in successive periods; such stars are known as regular variables, and their brightness at any future time can be predicted with mathematical exactitude. In the second class are the stars known as irregular variables; their periods are never the same nor is the particular series of light-changes exactly reproduced in succeeding periods. Variable stars are further sub-divided as follows: long-period variables, eclipsing variables, Cepheids, and new (or temporary) stars.

The best-known long-period variable is Mira Ceti, at times a prominent star in the constellation of the Whale. The variation in its light was first noticed by an amateur astronomer, Fabricius, in 1596. At its brightest this star may be as bright as a star of the second magnitude; it then gradually fades away and is soon lost to naked eye vision. If it is followed by telescopic observations, it will be seen to become as faint as a ninth or tenth magnitude star; it then gradually begins to increase in brightness, soon becoming visible to the naked eye and eventually reaching perhaps the third magnitude. The interval between two successive peaks of brightness (or maxima, as they are called) is, on the average, about 330 days, but there is no constancy as regards this value. At one maximum, the star may reach the second magnitude, at another, the third or fourth; and there is a similar uncertainty as regards the minimum brightness.

Eclipsing variables, as their name suggests, owe the observed fluctuations in brightness to the periodic eclipsing, or covering up, of one star by another. Let us first consider the way in which the light of a typical member of this class is observed to vary. We shall suppose that measures are made of the star's brightness at frequent intervals; from these measures we obtain the magnitude of the star at the corresponding times of observation. We can represent the changes in magnitude on a diagram such as Fig. 6. We shall depict the actual results for the bright star Algol (Beta Persei). For most of the time this star is of magnitude 2·9. At definite times it begins to decrease gradually in brightness, and in about 5 hours reaches magnitude 4·2. It then begins to brighten up, and 5 hours later reaches its former magnitude 2·9. Suppose "zero-hour" is when the star reaches its minimum brightness at A (Fig. 6); 63¾ hours later there is an exactly similar minimum at B. Almost exactly halfway between A and B there is a minute change in brightness—this is shown by the slight dip in the light-curve at C. These changes are faithfully repeated in successive periods of 68¾ hours.

Let us now see how the variation in the light of such a star as Algol is interpreted. In the preceding chapter we discussed close double stars—spectroscopic binaries—whose double character is revealed by the spectroscope. We shall consider simply that one component of such a binary revolves around the other component. If the line along which we are looking towards the binary is exactly or nearly in the plane of the orbit, then at intervals during the period of revolution one of the stars will get in front of the other, thus cutting off part or all of the light from the star. Fig. 7,

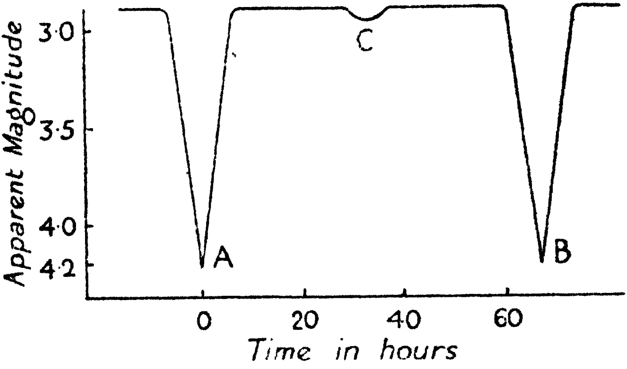

FIG. 6.

in which a star, B, is illustrated revolving round a star, A, serves to indicate how the expected changes in brightness of the system arise. There are two eclipses—one when B is in front of A, thus blanketing A wholly or partially, and the second when B is concealed by A. Clearly the diminution of light in either case will depend on the relative surface brightness of the two stars and also on their relative sizes. The study of such a light-curve as Fig. 6, interpreted in terms of eclipsing stars, furnishes some important information; for example, we are enabled to find the sizes of the two stars forming the binary in terms of their distance apart; in other words, we can construct a model of the system. With certain auxiliary information, furnished by spectroscopic observations in many cases, we can actually deduce the true dimensions of the stars.

The reader may inquire if there is any independent proof that the interpretation of the light-curve in the manner we have just indicated is justified. If Algol consists of two stars close together, the measures of radial velocity of one or both of the stars ought to show the cyclical changes characteristic of the spectroscopic binaries, and the velocity period ought to be identical with the light-curve period. It was Goodricke of York who, in 1783, first suggested that Algol is really a double star suffering periodic eclipses, a suggestion confirmed by E. C. Pickering in 1889 by means of radial velocity measures.

When both components of an eclipsing binary are sufficiently bright to record their spectrum lines on a photograph, we obtain the usual kind of information provided by spectroscopic binaries. Combining this information with that furnished by the study of the light-curve, we derive the general characteristics of the system. Let us consider, in particular, the eclipsing binary star "u Herculis," a star of apparent magnitude 4·5. The light-curve and the spectroscopic observations give the following results: The radii of the two components are 4·6 and 5·4 times the sun's radius; expressed in miles, the radii are respectively 2,000,000 and 2,340,000 miles (the sun's radius is 433,000 miles). The distance between the stars is 6,000,000 miles, and the period of revolution is just a little over two days. The star with the smaller radius has a mass 7 2/3 times the mass of the sun; the other component is almost 3 times more massive than the sun. The dimensions of the stars and their masses enable us to calculate the average density of the stellar material. The densities turn out to be about 1/7 and 1/30 that of water; expressed in terms of the average density of the solar material, the average densities of the two stars are about 1/10 and 1/48 of the sun's density respectively.

It was in this way that the dimensions of the stars were first measured. Within the last few years another method has been developed at Mount Wilson Observatory. We know that the sun subtends at the earth an angle of about 32 minutes of arc. If the sun were removed to a distance equal to that of the nearest star, the angle subtended by its diameter would be about 1/130 of a second of arc. This gives some idea of the minuteness of the angles subtended at the earth by stellar diameters. Nevertheless, with a specifically designed instrument, called the interferometer, the astronomers at Mt. Wilson have succeeded up to the present in measuring the angular diameters of seven stars. For example, the angle subtended by the diameter of Arcturus at the earth has been found to be 1/50 of a second of arc; the distance of the star is known (it is 40 light-years), and so the dimensions of the star can be easily calculated. Arcturus proves to have a radius of nearly 12,000,000 miles, about 27 times the radius of the sun. We shall return to the subject of stellar dimensions in Chapter VI.

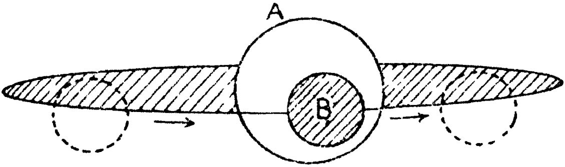

FIG. 7.

The Cepheid variables are so called after their prototype, Delta Cephei. Cepheids are regular variables, and their brightness at any time can be predicted with perfect accuracy. The name "Cepheid" is sometimes only applied to stars of this particular type with periods exceeding a day; stars with periods less than a day are known as "cluster variables," as they are mostly to be found in the great star clusters. Let us consider more particularly the phenomena associated with Delta Cephei. The light of this star undergoes regular changes in the course of about 5 days 9 hours. At its brightest, it is of magnitude 3·7, and at its faintest it reaches magnitude 4·6; thus at minimum it is not quite one half as bright as at maximum. The rise from minimum to maximum is comparatively rapid; only 30 hours are required for this stage in the light variation. The decline from maximum to minimum occupies about 4 days and 3 hours. So much for the main characteristics of the light-curve. Spectroscopic observations show that the character of the spectrum alters during the period of light changes. In particular, at maximum the lines due to ionised metals are unusually strong, indicating that the physical conditions then existing in the star's atmosphere are more than usually favourable for the ionisation of the metallic vapours concerned. Again, the wave-lengths of the spectrum lines are found to vary during the period; if these changes are interpreted in terms of radial velocity, the observations appear to show that the star's atmosphere is swelling outwards at or near the time of maximum light and contracting at or near the time of minimum light (it is generally believed that a Cepheid is not a binary but a single star). In favour of the statement just made, one of the arguments is as follows. If the light-curve is analysed on the assumption that Delta Cephei is an eclipsing binary, the model of the system that emerges is very different from the model of such a system as Algol, for the distance between the centres of the two hypothetical components is less than the sum of their radii; in other words, one component must be wholly or partially within the other. Whatever theory we invent with which to account for the light and spectrum changes of Cepheids, it seems certain that we must dismiss the hypothesis of a binary structure for these stars. The belief which is generally held amongst astronomers to-day is that a Cepheid is a pulsating star, alternately swelling and contracting in a regular kind of way. This explanation fits many of the facts; we mention but one. An increase in the star's radius implies an increase in the surface from which the streams of light and heat are radiated into space. Other things being equal, an increase in surface area means an increase in brightness. There is, of course, an important factor, namely, the possible decrease in surface intensity (that is, brightness per unit area of surface) as the gaseous globe is swelling. But even then the observed light fluctuations are satisfactorily interpreted on the pulsation hypothesis.

But the most notable discovery relating to Cepheids remains to be mentioned. From a study of numerous variables in the Magellanic Clouds (which appear to the naked eye as misty patches of light in the southern Sky) Miss Leavitt discovered that there existed a definite relationship between the average magnitudes of the variables and their periods. The Clouds are so far away that for practical purposes we can regard these variables as at the same distance from us. If the average apparent magnitude of one variable is, say, 12, and that of another 17, the first is thus 100 times more luminous than the second. The average apparent magnitudes provide, then, a reliable indication of the relative luminosities. It was found that the longer the period of the variable, the greater is its luminosity, and the increase of luminosity with period was shown to follow a definite empirical law, known as the *period-luminosity* relationship. It is evident that if the distance of any one variable is known, the absolute magnitudes of all others can be obtained. This has been done for the several of the nearer Cepheids. Although the physical reasons why a more luminous Cepheid should pulsate in a longer period than a less luminous variable are still somewhat obscure, the period-luminosity law is a powerful weapon for estimating the distances of such clusters and nebulæ in which the variables are found. This may be understood more clearly from the following considerations: Numerous photographs of, say, a star cluster containing one or more Cepheids, will furnish the evidence from which the periods of the light-changes of these variables can be deduced. The measures of the stellar images on the photographs will lead to the average apparent magnitudes of the Cepheids. The period being known, the absolute magnitude of any Cepheid is then deduced from the period-luminosity relationship. We now know the absolute magnitude of a variable (that is, the magnitude it would appear to have if it were 32½ light-years distant from us) and the photographs provide its apparent magnitude. A simple calculation will then yield the distance of the Cepheid or of the cluster of which it is a member. In the next chapter we shall discuss more fully the application of this method to the measurement of the distances of the remote clusters and nebulæ.

A *nova*, or "temporary," star is one that rises with almost startling rapidity from insignificance in the sky to comparative and, in some instances, unrivalled, splendour; thereafter, it slowly fades away towards its original insignificance. The historical records show no more brilliant nova than the star associated with the name of the distinguished Danish astronomer, Tycho Brahé. On November 11, 1572, this star rapidly attained such brilliancy that it was easily visible in broad daylight; then it was actually brighter than Jupiter or Venus when most conspicuous in the sky. In three months it faded gradually to the first magnitude, and by March, 1574, it was just visible to the naked eye. The telescope had not then been invented, and so its subsequent history can only be conjectured. Since Tycho's time, some 70 novæ have been discovered in the stellar system, most of these appearing in or near the Milky Way. Frequently the investigation of old photographs enables us to glean definite information as to the star's brightness before the outburst which carried the star to the pinnacle of its short-lived grandeur. The very bright nova which appeared in the summer of 1918 in the constellation of the Eagle rose within two or three days from the eleventh magnitude to a brilliance which was surpassed only by Sirius, the brightest star in the firmament; thus, at the peak of its glory, Nova Aquilæ (as this star is designated) was about 50,000 times brighter than it was before the outburst. Although the discoveries of novæ in the last three and a half centuries only average one in every five years, it is certain that the appearances of novæ are more frequent than these figures suggest. It is only those that attain a position of prominence in the sky that are generally " discovered "; a nova which reaches, say, the tenth magnitude at maximum, stands very little chance of being detected at the time, although the examination of photographs may, at a later date, lead to the inference that a star had blazed up only to fade away subsequently into insignificance. In the great nebula of Andromeda, some 86 novæ have been discovered, and it is estimated that if a continuous watch were kept, about thirty would be found on the average every year. Any theory which tries to explain the celestial catastrophe which results in a nova must take into account the comparative frequency of the phenomenon.

The distances of several novæ have been measured. The most reliable estimate refers, perhaps, to Nova Persei (1901). This star is about 330 light-years distant. The outburst took place about the time of the defeat of the Spanish Armada, and the news, transmitted on the wings of light, did not reach us till 1901.

The spectrum of a nova undergoes a series of changes of a complicated nature, and these changes are generally observed in all typical novæ. In particular, shortly after maximum, the nova spectrum shows bright, broad lines having the appearances of bands, which are displaced greatly towards the violet end of the spectrum in comparison with the corresponding laboratory lines of the known elements by which they are produced. The interpretation is that *the star is rapidly expanding with a speed that may be* as great as the stupendous one of 2,000 miles per second.

Any adequate theory of the cause leading to the blazing up of a nova must be able to account for the sequence of changes observed in the nova spectrum and for the liberation of the immense volume of heat and light radiated during the outburst; moreover, novæ are not infrequent phenomena, and so the explanation must not be such as to make the appearance of a nova a most unlikely occurrence. Various theories have been put forward from time to time. The collision of two stars would undoubtedly provide the liberation of radiant energy on the scale witnessed in nova outbursts, but from what we know of the distribution of the stars in space, and of their velocities, collisions must be so infrequent as to rule out this theory of the genesis of the nova. A star contains deep within its interior vast supplies of energy which are tapped just to the extent of providing the energy radiated from the star's surface into space. If a part of this internal energy could be suddenly released, a luminous outburst such as that seen in a nova might be expected. Such a release, it has been suggested, might be caused by a body of planetary size falling into the star and puncturing, as it were, the stellar layers which hold the internal energy in check. But we have no knowledge of such planet-like bodies coursing about in space, and such an explanation is somewhat in the nature of speculation.

But we have evidence of vast clouds of obscuring matter in space—gaseous nebulæ of great tenuity—and, moreover, in the case of several novæ these objects are seen, long after the outburst, to be surrounded by such nebulosity. The most recent theory of novæ depends on the collision of a star with the enormous target presented by a tenuous and extensive nebula. For reasons into which we need not enter here, the star must be supposed to be a dwarf star with a surface temperature round about 3,000° C. Such a star is intrinsically very faint, and at a distance of a few hundred light-years its apparent magnitude would be comparable with that observed in the case of several novæ before their outburst. In its passage through the nebula, the star would gather round it an envelope of the nebulous material which would act as a kind of blanket, preventing part of the normal supply of light-energy from the star's surface escaping into space. The clouds on our own terrestrial atmosphere at night act in much the same way; during the day, the surface of the earth is heated by the sun's rays, and if there are clouds at night, this heat is, to a great extent, enclosed by the cloudy blanket and so prevented from being radiated away into space. But the accumulation of energy between the stellar surface and the enveloping blanket cannot go on for ever, and there comes a time—perhaps a century or two after the star's penetration into the nebula—when the imprisoned energy bursts its bonds and the faint dwarf blazes forth into a brilliant nova, and after a brief hour of magnificence returns gradually to its former feeble state. Dwarf stars are abundant and nebulæ are abundant, so that this theory is sufficient at least as regards the frequent occurrence of novæ in the heavens, and, on the whole, it fits the other observed facts very well. Also, it may be added, there is every possibility that a star may enjoy the excitements of the nova stage on more than one occasion.

CHAPTER V

STAR CLUSTERS AND NEBULÆ

As we have seen in the previous chapter, the stars are not all single individuals pursuing independently their destinies in the universe, for a large proportion of the stars that appear single in the sky are on closer inspection, visual or spectroscopic, found to be double-star systems, the components of which are bound together by the ties of mutual gravitational attraction. Many triple and quadruple systems are known. Capella, the brightest star in our northern heavens, is a close double star (a spectroscopic binary), and some little distance from it in the sky is a faint star of the tenth magnitude at the same distance and moving with the same velocity as Capella. The three stars are thus in close association, and there are many other instances of a like character. The reader is probably familiar with the group of stars known as the Pleiades; six or seven are easily visible to the naked eye, and the number is greatly multiplied in the telescope. Those stars apparently are members of a definite agglomeration like the individuals in a flight of birds. This supposition can be put to the test; actually it is found, for example, that the Pleiades stars are moving in the same direction and with the same speed, and there is thus no doubt that they are moving through space as a comparatively compact formation in much the same way as a flight of migrating swallows traverses the continents. Such a cluster as the Pleiades is known as an *open cluster*. The open clusters are thus subsystems in the infinitely greater system of stars to which we attach the name of the *galactic system*.

Much more compact are the great globular clusters, of which about ninety are known. The magnificent cluster in the constellation of Hercules appears to the naked eye as a misty object; in the telescope it is seen to consist of almost countless stars apparently as tightly packed together as bees in a swarm. Long exposure photographs show that the number of stars in this cluster must be at least 100,000. The apparent compactness of the globular clusters can mean only one thing: they must be at stupendous distances from us. The discovery of Cepheid variables in these clusters opens up a way of deducing their distances. We have seen that there is a definite relation existing between the period of light variation of the Cepheids and their average absolute magnitudes or luminosities. From a series of photographs of a cluster such as the great cluster in Hercules the period of any Cepheid can be deduced and also its average apparent magnitude during the cycle of light changes. From the relation just mentioned and the observed value of the period of light variation, the average luminosity or absolute magnitude of the Cepheid can be inferred. As the absolute magnitude is the magnitude the star would have if it were situated at a distance from us of 32½ light-years, and as we know from the observations its apparent magnitude, a simple calculation enables us to deduce its distance. To take an example: from the relation between period and luminosity, it is believed that a Cepheid with a period of 1 day has, on the average, an absolute magnitude of −0·5 approximately; suppose that in a cluster there is a variable with this period and an average apparent magnitude 14·5. As there is a difference of 15 magnitudes between 14·5 and −0·5, and as a difference of 5 magnitudes corresponds to a distance ratio of 10 to 1, we infer that the star must be actually 10 × 10 × 10 or 1,000 times the standard distance of 32½ light-years—that is to say, the star must be 32,500 light-years from us. This was the principal method of attack adopted by Shapley at Mt. Wilson Observatory in his studies of the distances of the globular clusters. The nearest globular cluster proved to be the great cluster in Centaurus in the southern sky at a distance of 20,000 light-years; the great cluster in Hercules is 35,000 light-years distant from us and the most remote is about 230,000 light-years from us. From their apparent sizes in the sky and from their measured distances it is but a step to calculate the true dimensions of these objects. Their diameters are of the order of several hundreds of light-years and within a sphere of such diameter are congregated thousands and perhaps hundreds of thousands of stars. It is to be remembered that it is only the comparatively luminous stars in the cluster that appear on the photographs; the dwarf stars of a luminosity not exceeding that of the sun are too faint, owing to their great distance from us, to register their images on the photographic plate. We do not know, of course, that the clusters do contain feebly luminous stars; but if the range of stellar luminosities in the globular clusters is even roughly comparable with the range observed in the galactic system it must seem that the clusters are indeed densely populated. Many of the clusters have large radial velocities of approach, and this fact has suggested that the open clusters are the remains of globular clusters that have penetrated the galactic system and all but lost their characteristic compactness owing to encounters with the vastly superior numbers of galactic stars. The distribution of globular clusters is remarkable; with hardly an exception they are to be found in one hemisphere of the sky only. If we regard the clusters as forming a system in space, this fact, just alluded to, must mean that the sun is far removed from the centre of the cluster-system. Other considerations combine to show that the sun is a long way from the centre of the galactic system, and the distribution of the clusters in space has suggested that these clusters represent the limits within which the galactic system of stars lies. In this way Shapley has estimated the extent of our lens-shaped system of stars—the longest diameter is about 300,000 light-years and the shortest about 50,000 light-years. In pre-Copernican astronomy the earth was supposed to be the centre of the universe; Copernicus and Galileo stressed the importance of the sun, of which the earth is but an almost insignificant dependent; modern research now puts the sun far from the centre of the stellar universe, and regards it as but a feeble star in a galaxy teeming with millions of brilliant orbs.

The nebulæ can be divided broadly into two classes—irregular and regular. In the first class are the luminous nebulæ, of which the Great Nebula in Orion is perhaps the best known and most beautiful example, and the dark nebulæ; in the second are the planetary nebulæ, the spiral nebulæ, and the globular and spindle nebulæ. Let us first consider the diffuse irregular and luminous nebulæ. In addition to the marvellous Orion nebula, we mention the beautiful Trifid nebula in the constellation of Sagittarius with its radiating dark lines, the filamentary nebula in Cygnus, with its beautiful and delicate tracery, and the North America nebula, so called because of its striking resemblance in form to the North American continent. In constitution the nebulæ of this class are gaseous. Dr. Hubble at Mt. Wilson Observatory has adduced very convincing arguments to show that these gaseous nebulæ are not self-luminous, but that their light is derived from brilliant stars in their neighbourhood. The planets, we know, shine by the reflected light of the sun, and reflection of the light from neighbouring bright stars may account in part for the apparent brightness of the nebulæ. But this is not all. It is certain that the gas of which these nebulæ are composed is of a density very much feebler than that of the unexhausted gas in the most efficient terrestrial vacuum; in this condition the atoms of the constituent gas or gases are widely scattered and little able to interfere one with another. The radiation from the associated star is able to stimulate the atoms to luminescence and to this fact the visibility of the nebulæ is mainly if not entirely due. The diffuse nebulæ associated with the hot B type stars show bright lines in their spectra; when the stars are of later type, the spectrum is continuous with dark absorption lines. But what makes the spectra of many nebulæ noteworthy is the presence of several bright lines—in particular, two in the green part of the spectrum, to which the greenish appearance of the nebulæ in the telescope is to be attributed—whose origin, until recently, was supposed to be due to an unknown substance provisionally named nebulium. The chemist and the physicist and the astrophysicist were confident that the origin of these lines was not to be explained in terms of an undiscovered element; they believed that one or more familiar terrestrial elements were masquerading in some mysterious way with which science had not been previously acquainted. Towards the end of 1927 the problem was solved by Dr. Bowen of Pasadena, who showed that the mysterious nebulium was only oxygen and nitrogen, the atoms of which were ionised and, under the peculiar density conditions, able to emit the characteristic bright lines that proved so baffling to two generations of astronomers. The corona, visible only during total solar eclipses, presents a similar problem, for the spectrum of the lower corona, contains several bright lines of unknown origin. Recently it has been suggested that the inert gas argon is responsible for these lines, and although the chain of reasoning appears to have some links of doubtful strength, yet it is certain that the unknown "coronium" will eventually be traced, if not actually to argon, then to one or more of the common terrestrial elements.

In the Milky Way the stars are scattered in rich profusion, for in these directions we are looking towards the most distant parts of the stellar universe. But every now and then as the telescope sweeps over the Milky Way we come to regions where the stars suddenly seem to come to an end. Barnard's beautiful photographs of the Milky Way show numerous dark areas and markings in which there is hardly a star to be seen. These dark areas are undoubtedly due to vast clouds or dark nebulæ which obscure the light of the stars beyond. It is unlikely that the dark nebulæ are in any way different, as regard constitution, from the diffuse luminous nebulæ which we have just been considering; the beautiful forms of the latter are only revealed owing to the stimulating effects of bright stars which happen to be near them. We must recognise, then, that vast tracts of space are filled with obscuring nebulæ, thinning out in all directions to such a density that their effects are hardly noticeable. In certain instances the existence of matter in interstellar space can be inferred, although visual observations and long-exposure photographs give no clue to it. Many spectra of spectroscopic binaries of class B show, in addition to the double lines undergoing their periodical changes in position, certain "fixed" lines invariable in position, notably the H and K lines of ionised calcium and sometimes the D line of sodium. The spectrum of such a binary furnishes amongst others things, as we have seen, the radial velocity of the system; the "fixed" lines furnish the radial velocity of the substance to which they are due. In every case examined it is concluded that the calcium, for example, is practically at rest in space, and that the measured radial velocity derived from the "fixed" lines is simply the effect of the sun's rushing through space (or the calcium cloud) with the speed of 12 miles per second. The calcium thus forms as it were a vast interstellar cloud of incredible tenuity. But it must not be supposed that in interstellar space there are only calcium and sodium atoms. The atoms of other elements do not react to the particular qualities of the radiation from the stars in the same way as the atoms of calcium and sodium. Space then must be pictured as being inhabited by stray atoms of several elements at least: in places they congregate thickly, forming the obscuring nebulæ: some of these vast condensations are in the neighbourhood of luminous stars and are thus made visible to us in the beautiful forms that delight the eye and stimulate the imagination.

The planetary nebulæ, of which over a hundred are known, are small objects in the telescope. The Ring Nebula in the constellation of Lyra is perhaps the best known; it appears as a broad, luminous ring with a star at the centre. Most of the planetaries have central stars, and in over a score of instances the distances of these stars and therefore of the nebulæ have been measured. These objects are conceived to be vast globes of rarefied gas surrounding the central stars, the radiation from which is able to make the gaseous envelopes wholly or partially luminous. The dimensions of the planetaries are easily derived when once their distances have been measured; it is found that their diameters are at least 100 times the diameter of the solar system. (The distance between the sun and Neptune—the most distant planet—is about 2,800 million miles.) The spectroscope shows that the planetaries are rotating slowly and in their spectra are to be found the bright lines for so long attributed to nebulium.

The spiral nebulæ form a very numerous class. The great spirals are very magnificent objects, best studied in long-exposure photographs. It is generally believed that spirals are flat systems, in their dimensions resembling a lens. Their appearance will consequently vary according to the angle which their principal plane makes with the direction in which we view them. In some instances we obtain what may be described as a bird's-eye view of the flattened systems; in other instances we see them edge on. The principal features of a typical spiral are, firstly, an extensive luminous nucleus, and, secondly, a pair of spiral arms which, starting from opposite parts of the nucleus, bend round in spiral curves which in many instances can be followed for a complete revolution or more. The spiral arms are not continuous; they consist rather of hazy knots of light, which may be nebulous masses or clusterings of stars, as well as innumerable single stars strung out along the spiral curves. The question immediately presents itself: " What is the constitution of a spiral nebula?" This question can be answered more satisfactorily if we can form some reliable estimate of the distances at which these objects are from us. Until recently astronomers were divided as to the place of the spirals in the universe; they could either be bodies within the great galactic system of stars or alternatively they must be regarded as vast systems very much more remote than the most distant stars of the stellar system. The second hypothesis implied that the spirals are independent systems to which the dignity of the title of " island universes " was believed to be appropriate. Let us consider the various lines of evidence which seem to point unmistakably to the conception that the spirals are independent or " island " universes scattered about in the ocean of space.

The spirals are found in all parts of the sky except in or near the Milky Way. Now the Milky Way is the region in which the great obscuring masses are found, and it is therefore not surprising that, if the spirals are really at great distances, they are not visible in Milky Way regions owing to the blanketing effect of these dark nebulæ. Again, the spectra of the brighter spirals resemble the spectra of stars of class G—that is to say, their spectra consist of the continuous spectrum crossed by a large number of absorption lines. One inference is that the spirals are really—in the main, at least—aggregations of stars. The radial velocities of several spirals have been measured and these are incomparably greater than the velocities of the different objects—stars, diffuse and planetary nebulæ—of the galactic system. Over 80 per cent. of the radial velocities are velocities of recession, and the greatest so far measured is the stupendous velocity of about 1,100 miles per second. The evidence from the radial velocities seems to place the spirals in a category by themselves. The measurement of the distances of the nearest spirals is based on the discovery of novæ (or " new stars ") and Cepheid variables in these objects. The study of the distances and the maximum apparent magnitudes of novæ appearing in the galactic system gives us some idea of the luminosity attained by these stars at maximum. If it is assumed that the numerous novæ which have been discovered, for example, in the great spiral nebula in Andromeda are similar to the galactic novæ, it is possible, from the maximum apparent magnitudes of the novæ in the spiral to derive a reliable estimate of its distance. But the most conclusive evidence as to the vast distances of the spirals has been provided by Dr. Hubble at Mt. Wilson from his study of Cepheid variables, which he has discovered in these objects. We have explained briefly how the distances of the globular clusters have been measured by means of Cepheids; in a similar way Hubble has derived the distances of two spiral nebulæ—the great nebula in Andromeda and the beautiful spiral in the constellation of the Hunting Dogs. These nebulæ are each at a distance from us of about 900,000 light-years. Moreover, long exposure photographs of part of the Andromeda nebula show that what at first sight appears to be hazy nebulosity is in reality a vast swarm of very faint stars. When the distance of the nebula is known, its dimensions can then be calculated. The Andromeda nebula proves to be a vast system, about 45,000 light-years across its longest diameter; it is thus a system comparable with the galactic system of stars and fully deserving of the title of "island universe." The telescope reveals thousands of spirals, apparently very minute compared with the magnificent Andromeda nebula; these, it must be inferred, are at still more stupendous distances from us. Modern astronomy has given us an almost terrifying picture of the vastness of the universe. Long before the appearance of the human race upon the earth the light from the great spiral nebulæ has been silently pursuing its way through the immensities of space and after a million years or more it finally reaches this insignificant earth of ours to tell us now of happenings in the inconceivably remote past.

CHAPTER VI

THE EVOLUTION OF THE STARS

WHEN we look at the sun or the myriad of stars that adorn the firmament, even the least imaginative of us must sometimes ask, "What is the origin of the sun and stars, and what is the eventual fate of the Universe itself?" Here is a problem of surpassing interest and obviously of tremendous difficulty that astrophysics sets itself to solve. Let us first consider briefly the modern ideas concerning the birth of stars. The diffuse nebulæ, whether dark or luminous, whether gaseous or composed of fine dust, as some astronomers are inclined to believe, have evident potentialities as to the parentage of stars. A diffuse nebula must gradually contract and become hotter under the mutual gravitation of its parts, and it is quite conceivable when the process has proceeded far enough, that the condensations will become self-luminous stars. But we have to look to the great spiral nebulæ as the most fruitful sources of the stars. According to the theory advanced by Sir J. H. Jeans, the great nebulæ assume, as a result of rotation (which in many instances has been observed), a flattened shape something like a lens, and nebulæ of this form are known. Without going into any detailed account of the arguments, the lens-shaped nebulæ are believed to develop into the spiral type, throwing off vast masses of gas to form spiral arms, which subsequently condense into individual stars or clusters of stars. So much for the origin of stars from the primordial nebulæ. Is it possible to follow the subsequent history of the stars now embarked upon a luminous career? It is, of course, impossible to observe the development of any one star, for even the complete interval of time during which the human race has existed on the earth is but as a moment in the life of a star. The method of approach to the study of stellar evolution is founded upon the various observed characteristics of the stars, and on the presumption that, as a star gets older, its characteristics, such as mass, density, surface temperature, change in some definite way.

The spectral series (spectrum classes B, A, . . . M) suggest the reign of order in the course of a star's development, for the series is one of decreasing surface temperature. Before 1913 it was generally believed that a star, early in its career, was of class B, and that the succeeding classes represented stages in its subsequent evolution. But the discovery of Dr. E. Hertzsprung and Professor H. N. Russell that the red stars, for example, of spectral class M, consisted of two distinct groups, one of exceedingly great luminosity and the other of feeble luminosity—the giants and the dwarfs—revolutionised completely current ideas concerning a star's evolution. A giant of class M must owe its great luminosity to immense bulk; the feebleness of dwarf M stars must be due to their comparatively small dimensions. The interferometer measures of the angular diameters of the red stars Betelgeuse and Antares, together with their known distances, reveal to us stars with diameters two or three hundred times the diameter of the sun and with volumes more than a million times the volume of the sun. The diameters of the red dwarfs derived from other considerations, on the other hand, are no more than one quarter of the sun's diameter. In spectral classes G and K the separation of the stars into giants and dwarfs is similarly a well-attested fact of observation, although the disparity between a giant of class G, for example, and a dwarf of the same class is not so pronounced as in class M. In class F, the distinction between giants and dwarfs is still less conspicuous, and in the remaining classes A and B, any disparity practically vanishes, and the stars, being of high luminosity, can all be described as giants. In 1913, Professor H. N. Russell advanced the theory of stellar evolution which definitely held the field for over ten years. The youngest stars of all are supposed to be enormously distended red giants like Betelgeuse, formed, as suggested at the beginning of the chapter, on the contraction of a nebula. But contraction does not cease. The gaseous globe goes on shrinking and, as it contracts, the amount of heat energy contained in the star increases, and this is reflected in a higher surface temperature. The stellar material is, of course, all the while increasing in density. During this process the decrease in luminosity due to the reduction of the surface area of the star is about counterbalanced by the increase due to the greater brilliancy of each square inch of surface resulting from the higher surface temperature; the star in consequence does not change very much in luminosity. In this way the giant red star is conceived to develop successively into a K class giant, a G class giant, and so on until class B is reached. At this stage the density of the stellar material is believed to be so great (about 1/10 that of water) that the subsequent contraction becomes increasingly difficult, so that the star gradually cools, and so it passes from the B class through the spectral sequence B, A, . . . M, eventually arriving at the red dwarf stage. Beyond this point we can only surmise that the star gradually fades away as a self-luminous body, finally becoming a "dark star." This scheme of evolution is illustrated in Fig. 8. Under the spectral types are placed the approximate surface temperatures; the diminishing series of circles (following the direction of the arrows) represent the diminishing sizes of the star in its suggested evolutionary history. This theory was supported by a mass

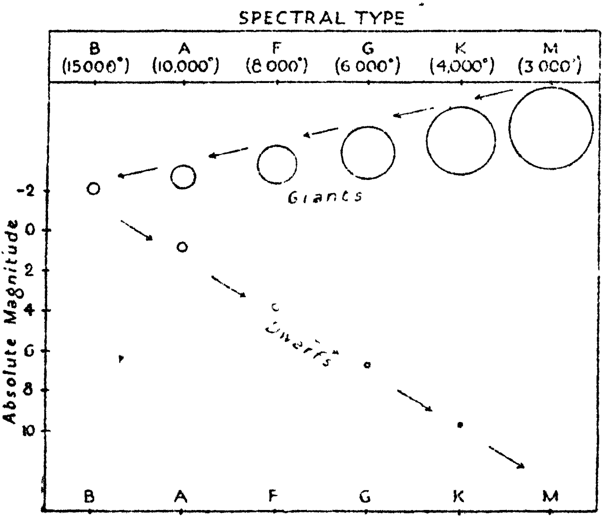

Fig. 8.

of evidence, and the course of events could even be followed—at least, from the giant M stage to the B stage—by mathematical analysis.

Let us consider briefly the main points in the mathematical problem. Assume that the material of which a giant star is composed is gaseous and amenable to the physical laws pertaining to what is known as a " perfect gas." In such a gas the atoms, or, as we shall describe them, the particles, are widely scattered, occupying a very small proportion of the space through which they are free to roam. In a dense gas, the particles are more tightly packed together; if the gas is liquefied, the particles become almost jammed one against another. A giant star is then conceived as a vast globe of gas with the properties summarised in the term "a perfect gas." Besides density, there is another property of a gas which must be considered—namely, pressure. This may be best exemplified in the case of a balloon. The gas particles within a balloon tend to press outwards, and the pressure on the containing substance becomes greater as the number of gas particles, forced inside the balloon, increases. At a point within a star, the gas there has to press outwards to balance the weight of the gas above, which is, of course, pressing inwards; the further we go within the star, the greater is the weight to be supported, and therefore the greater is the pressure of the gas required to maintain a balance. Also, the density of the gas increases as we go inwards. Putting it another way, we can say generally that the number of gas particles within a cubic inch of space increases as we go inwards towards the centre of the star. But in an actual giant star, heat and light are pouring from its surface outwards into space; this radiation originates within the star, and the inference must be that the temperature of the stellar material increases with depth below the surface. This increase in temperature comes to the assistance of the gas pressure at any point in its task of supporting the weight of gas above; for the hotter the gas is, the greater is the pressure that it can exert. It is believed that at the centre of a star the temperature is to be measured in millions of degrees. A new agency comes then into play. It is known that light exerts a pressure which can be measured. Under the conditions prevailing within a star, this light pressure, or, more generally, radiation pressure, assumes considerable importance, and its effect must therefore be considered in conjuction with the ordinary gas pressure which, as we have seen, depends primarily on the density and temperature of the gas. There is another physical conception involved in the problem. Just as a material particle within a star finds difficulty in forcing its way outwards owing to the gaseous particles in its path, so the radiation within the deep interior is restrained by the layers above from a sudden dash to freedom beyond the stellar surface. Finally, within the star, the temperature is so great that an atom of such an element as sodium cannot retain its system of electrons; the atom is ionised almost or quite completely, and instead of a single atom of sodium, there are twelve independent particles, one the sodium nucleus and the remainder the planetary electrons. The average weight of these independent particles, which we must imagine rushing about within the star, is just a little over twice the weight of the hydrogen atom, and this result holds generally for the other chemical elements, with the exception of hydrogen itself. This conception of the more or less complete ionisation of the chemical elements renders unnecessary the consideration of the chemical constitution of the star. Such, in brief, are the main features in the mathemateical problem considered by Professor Eddington. Suppose that the mathematician starts with a globe of gas, isolated in space, with a mass equal to that of the earth. Calculation shows that the temperature will increase very slowly within such a globe and that radiation pressure at any point—which depends, of course, on the temperature there—is entirely insignificant. The globe, in fact is virtually incapable of radiating any appreciable quantities of heat and light, and consequently it cannot become self-luminous like a star. In Chapter I. we stated the mass of the sun in tons. Consider, now, a globe of gas with a mass 1/10 that of the sun. The calculations now show that radiation pressure becomes an appreciable fraction of the gas-pressure, and that the amount of radiation emitted across the surface of the globe will be such as to render the globe faintly self-luminous. It is significant that no star is known with a mass less than 1/10 of the solar mass. With greater masses, radiation pressure rises into still greater prominence in comparison with the gas pressure, and when we reach a globe with a mass 100 times that of the sun, radiation pressure practically assumes complete responsibility in supporting the weight of the stellar material, and beyond this mass it is believed that no globe can remain stable under the enormous outward pressure of the radiation. Now, it is precisely within these limits—1/10 and 100 times the solar mass—that the observed masses of the stars are found to lie. As regards mass, nature allows very little latitude in her building-up of the self-luminous stars.

The calculations to which we have been directing the reader's attention apply to giant stars, the material of which is, without any doubt, in the condition of a perfect gas. What can be said about a dwarf star, like the sun, where the solar material has an average density 1½ times that of water? It is found that the theory fits the observed facts relating to dwarf stars as satisfactorily as for the giant stars. There can only be one conclusion—the material of the sun must be in the condition of a perfect gas. At first sight this seems an absurd inference. In a terrestrial gas, say, our atmosphere, the atoms of oxygen and nitrogen resemble miniature solar systems; and just as the dimensions of the solar system are stupendous in comparison with the dimensions of the sun and of the individual planets,* so each atom occupies a volume exceedingly great compared with the volume occupied by the nucleus or by a single electron. Now, within the stars—giants and dwarfs alike—the chemical atoms cannot exist as complicated electronic structures; they are stripped of their electrons perhaps right down to the nucleus; the individual particles constituting the stellar material are no longer the comparatively bulky atoms, but the bare nuclei and electrons. In a terrestrial perfect gas, the freedom of movement of an atom depends on the ratio of the atomic dimensions to the average distance from neighbouring atoms. When the gaseous particles are nuclei and electrons, a comparable freedom of movement of an individual particle can be achieved even if the nuclei and electrons are thousands of times more tightly packed than the atoms in the terrestrial gas. Hence it comes about that the stellar material, even if it is many times denser than water, can still be regarded as a perfect gas. This one comprehensive theory takes under its wing both giant and dwarf stars alike. (The white dwarfs whose average density is at least 50,000 times that of water, must be excepted from this general statement.)

But the main point of the theory in its relation to the evolution of the stars is this. Observation and theory agree that the most massive stars are the most luminous, and the stars of least mass are the least luminous. If we refer to Fig. 8, we see that a process of evolution that carries a star from the giant M stage, along the giant branch, and thence down the dwarf branch (following the arrows) eventually to reach the dwarf M stage, must mean that the star is getting rid of a large proportion of its mass during its evolutionary career; for in the red giant stage, the stellar mass is probably 20 or 30 times, at least, greater than the mass of the sun, and if this star slowly evolves into a red dwarf, as suggested, its mass is then no more than a quarter of the solar mass. The question is: How can a star shed its mass? What we know that a star can and does shed is radiation—that is, light and heat energy. For the sun and stars this can be calculated. The theory of relativity identifies mass with energy and energy with mass. The sun, for example, radiates light and heat energy at a prodigious rate. Expressing energy in terms of mass, we can calculate that the sun is losing mass by radiation at the rate of 250,000,000 tons* per minute; for giant stars the rate is much greater, and for stars less luminous than the sun the rate is less. In Chapter I. we stated the present mass of the sun in tons; a simple calculation will give us, then, some idea of the interval required for a star, say, 10 times more massive than the sun, to become equal in mass to the sun. There are two questions now to be faced. Is this interval compatible with what we believe from other considerations to be characteristic of the age of the sun? And what is the physical process by which the sun or a star maintains its output of radiant energy at the expense of its mass? It is generally believed that the earth is an offshoot of the sun, and as reliable geological and other evidence assigns an age of about 1,300,000,000 years to the earth, the age of the sun must be still greater. This interval is much less than that required in the evolution theory based on the transformation of mass into radiation, and so we are led to the possibility that the age of the sun (since the time it was formed out of a nebula) is of the order of 7,000,000,000,000 years. To answer the second question, we must recognise that some drastic physical process appears to be absolutely necessary. This is believed to be the actual annihilation of matter within the deep interior of the star and its conversion into radiation; just as the result of throwing a lighted match on a heap of gunpowder is an intensely luminous flash, so in some similar kind of way the collision of an electron (with negative electrical charge) with a proton (positively charged) is conceived to result in the destruction of the mass of the proton and electron and its conversion into a flash of radiation, which finally is transmitted across the surface of the star into outer space as heat and light energy. An important factor in the problem is the rate at which an individual star converts its mass into radiation, for its needs are evidently governed according to the outflow of light and heat across its surface.

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* The distance between the sun and Neptune (the most distant planet) is 2,800,000,000 miles; the radius of the sun is 433,000 miles, of Jupiter (the largest planet), 44,000 miles, and of the earth, 4,000 miles.

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* This is just about the total yearly output of coal in Great Britain.

The problem of stellar evolution is at an interesting stage, but it is hardly possible in this brief sketch to discuss in greater detail the evolutionary theories of Eddington, Jeans, and Russell. In science the theories of to-day are decently interred to-morrow, and in the particular problem we have been considering, contemporary astronomy has glimpsed but little more than general principles. The facts of observation are the basis on which any theory must be judged, and in an intricate problem of this kind, the most pressing need is for more detailed information about the stars themselves. That the stars evolve from one type to another is more than an article of faith. The stupendous interval of time necessary for evolution—in other words, the stupendous figures which must be assigned to the ages of the stars—cannot seriously be denied on evolutionary or other grounds. The source of the amazing flow of light and heat from the stars must be traced to the stellar interiors, and the hypothesis that the source is the stellar material itself, which is slowly transformed into radiation, leads to implications in agreement with many of the familiar facts of observation. Our conception of the universe is one of twofold immensity—immensity in space and immensity in time. But that is not all. The material out of which the universe is made is slowly but surely melting away into radiation. Is there a reverse process—the conversion of radiation into matter? If not, the universe will be like a clock, slowly running down, without the faintest prospect of ever being wound up again.

BIBLIOGRAPHY

The following books are descriptive in character:

Abbott and Mitchell: *The Fundamentals of Astronomy.* (Chapman and Hall.)

Andrade, Professor E. N. da C.: *The Atom.* (Benn's Sixpenny Library.)

Eddington, Professor A. S.: *Stars and Atoms.* (Clarendon Press.)

Forbes, Professor G.: *The Earth, the Sun, and Moon.* (Benn's Sixpenny Library.)

Forbes, Professor G.: *The Stars.* (Benn's Sixpenny Library.)

Gregory, Sir R. A.: *The Vault of Heaven.* (Methuen.)

Lodge, Sir Oliver: *Atoms and Rays.* (Benn.)

Smart, W. M.: *The Sun, the Stars and the Universe.* (Longmans, Green.)

Whyte, Rev. C.: *The Solar System and the Stellar Universe.* (Griffin.)

The following books are of a more advanced type:

Dingle, Professor H.: *Modern Astrophysics.* (Collins.)

Jones, H. Spencer: *General Astronomy.* (Arnold.)

Russell, Duggan, and Stewart: *Astronomy:* Vol. I., *The Solar System;* Vol. II., *Astrophysics and Stellar Astronomy.* (Ginn.)

Stratton, F. J. M. *Astronomical Physics.* (Methuen.)

CHEMISTRY

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CHEMISTRY

By PERCY E. SPIELMANN

Ph.D., B.Sc., A.R.C.Sc., F.I.C., A.Inst.P., M.Inst.P.T.

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FOREWORD

The presentation of a comprehensive survey of a vast subject, compressed into a very limited space, and addressed to a public that is, in a great measure, unfamiliar with scientific matters, is a task of some difficulty.

It is hoped that this end has been reached in a manner that will be helpful in making precise in the public mind the nature and scope of chemistry, and in showing clearly its influence on the life of every individual as a personal protector, a foundation of our very existence and of our development, and the subject of a great profession.

In order that this little volume may be not less trustworthy and authoritative than the more exhaustive treatises on the subject, chapters have very obligingly been read by Professor H. Brereton Baker, C.B.E., F.R.S., of the Imperial College of Science and Technology, and by R. B. Pilcher, Esq., O.B.E., Registrar and Secretary of the Institute of Chemistry of Great Britain and Ireland, to whom I express my warm thanks for their valuable suggestions.

P. E. S.

May, 1927.

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CHEMISTRY

CHAPTER I

THE NATURE OF SCIENCE AND OF THE SCIENTIFIC MIND

THE spirit of inquiry is rooted very deep; it is far, far older than human nature. There can be no doubt that it began amongst the first animals that consciously tended their young and concerned themselves with their welfare. The procuring of food and the precautions for safety have been actively developed in them by the parents; these efforts can only be successful if the young are prepared to learn, and the young are prepared to learn through an instinctive curiosity and capacity for imitation. This is the basis of education in the young of all animals, including man; and in man the culmination of such education is the power of profound and logical thinking and of magnificent handicraft. Such high abilities have resulted from two causes or, rather, from two conditions that rendered them possible.

All animals, except the lower, possessed eyes placed so far apart that they acted independently in that they transmitted two separate images to the brain. At one stage of evolution an animal, which has been named Tarsier, had become possessed of eyes so close together that they could be focussed on to one spot, so that it obtained a greatly improved image of any object it wished to see. Tarsier is a little lemur-like animal with enormous eyes, out of proportion to the size of its head. At the same time associated changes occurred in the brain of the animal which enabled use to be made of this new condition, which has persisted and developed.

The other condition consisted in the adoption by certain proto-monkeys of an upright position. The front paws were no longer required for progression, so that they were thus set free to handle things and to perform such acts as the brain directed. The results of such acts gave the brain food for thought and thereby caused it to make new demands on the activities of the hands. And so, by action and reaction of brain and hands, supported by accurate vision, and stimulated by curiosity, man evolved.

The child is born with a sketch-map of a brain; this becomes developed by growth and training into a powerful organ of thought. The baby mind is empty of the knowledge that it begins to acquire from the moment of its advent into the world, and the collection that it makes is called "experience." Experience, such as is met with day by day, leads to the formation of character and "knowledge of the world"; it is by the organisation of facts forming knowledge that we achieve "science."

The fundamental meaning of this word is just "knowledge," but in our ordinary use of it a much deeper significance has been given to it. It is used for that section of human activities that takes the detailed facts of knowledge and experience, and arranges them in a definite and orderly fashion. They may be grouped in a number of different ways and be regarded from as many points of view as possible, whereby results are deduced that are of value for present use and future advance.

This scientific method is based broadly on certain assumptions, so deeply rooted and so firmly founded as to preclude doubt as to their validity.

There is, to begin with, the belief that modern science is an expression of the laws of Nature—natural laws that are logical and to be trusted for ever to give the same results when repeatedly examined under the same conditions. Supernatural activities, as such, are not recognised as science, though they may be investigated to find out how much, if anything, can be interpreted in a scientific manner.

Then there is the recognition of the unity of nature. Perhaps this is better described as being the continuity of nature. Every true fact that we meet—indeed, facts are only facts when they are true; like the little boy who asks you for " the *right* time "—every fact that we meet is not an isolated thing, but an intimate and significant and essential unit of the universe; and if it is not that, it is an error. Every new observation must be true and accurate under all conditions and in all juxtapositions. It does not come into the domain of human knowledge with the stamp of truth upon it; it has to be very thoroughly examined. It is but one piece of mosaic that must fit in to the great pattern—the Great Pattern of Nature; and if it does not fit, either it or the adjacent portion of the pattern is misshapen and wrong; one or other or both have to be modified, and when at last this does fit, the pattern is found to be more perfect. There is no such thing as contradiction among facts, or among the scientific laws or the generalisations according to which whole collections of facts co-operate.

An example of this is to be witnessed at the time of writing. For a long time the wave theory explained, with great perfection, the phenomena of light. Recent photo-electric experiments have yielded results that can only be explained by the theory of light consisting of a stream of some kind of separate particles. Each theory explains its own group of phenomena admirably well, and yet they do not harmonise one with the other. Each theory obviously contains a large proportion of truth, and yet they do not fit. Work is going on now that seeks to bring them together, and undoubtedly the complete truth will be the more wonderful from the union of the two more limited ones.

This conception of the Pattern of Nature, which is, actually, a very close if picturesque analogy, acts as a serious warning and safeguard when we are asked to accept some utterly strange idea that may be contrary to human experience and apparently opposed to natural laws. We are fully justified in adopting at least a waiting attitude to see if and when it " fits in."

The third fundamental assumption is the intimate and inevitable association between cause and effect. Everything that happens must have had a cause, or source; and it is this source that is ever being sought for each thing that is of interest to man. When the cause is repeated the same result and only the same result is obtained. If there is any change, then the cause has changed or has been incompletely identified.

Progress is slow and sure when we stick to these methods of realities, but diffuse, intangible, and ever to be questioned when we do not do so.

It is on principles such as these that the scientific man, of whom the chemist is our example, bases his method of work. Whatever may be his object—whether it is for the purpose of increasing the world's content of knowledge (without any clear view of the immediate practical value of such work) or for a directly industrial application—the immediate attitude of the worker is to observe and to interpret results of experiment, whether of routine analysis or of research, accurately and dispassionately; he strives with persistent purity of effort for the attainment of trustworthy results. If he does not preserve this high and moral attitude towards his work, he is a danger to the community and a traitor to his calling.

In the highest types of research final attainment seldom comes at once and often not by the efforts of one man alone. It may happen that, with whatever ease or difficulty experimental results are obtained, their interpretation and the assessment of their value as scientific evidence may be far more difficult.

This may even be impossible at the time of their discovery, because the rest of chemistry or, indeed, the state of the whole of science may not yet be ready for these new results; there may be too few tesseræ in that portion of the Great Pattern for the places of the new ones to be determined.

Whatever may be the state of these conditions, the various facts are collected together and, by induction, they are employed to formulate an hypothesis, a preliminary scientifically directed guess as to the most likely meaning of the observations. After an account of the new work has been published it will be repeated by some other investigator and be confirmed, modified, or disproved.

The best method of proving the truth of such an hypothesis is its employment as the basis for the logical deduction of some further possibilities, followed by the testing of these new ideas. If they appear to be fulfilled, the new hypothesis has received important support and has passed the tests of classification and generalisation.

By successfully surviving such scrutiny, the hypothesis becomes developed into a theory, which then has to sustain the most penetrating scientific criticism, and perhaps undergo modification, often for years, before it assumes the firm and unalterable condition of a scientific law, an established and fundamental piece of knowledge which, within the utmost limits of human capacity, can be adopted as being scientifically and absolutely true.

It is seen that, in the progress towards the establishment of scientific truths, advance can only be made by the most careful and cautious stages of practical experiments and mental deductions, each continuously fulfilling and stimulating the other. Under ideal conditions each step is carefully consolidated and proved before the next one is taken, so that there shall be no doubt as to the trustworthiness of the new progress. Experiments, their interpretation, and the use of this in devising new experiments constitute the scientific man's mode of progress, and happy is he who continues unbaffled. Sometimes, even often, such progress is not possible, and results of research are published for their own sake or are provisionally supported by assumptions to be dealt with later. In the worst case tentative progress is made by arguments based on analogy, a procedure which is fully recognised as being the most dangerous of all methods for seeking understanding, as it is superficial and often merely coincidental. To-day it may only be adopted in desperation as a temporary measure, though it constituted the main principle—and hindrance—for the alchemists.

It will have been realised that the way of the scientist is not smooth. When, at last, he has established his results on as firm a basis as is possible to him, his work is ever open to being retested and reviewed, in accordance with advances in other sciences or the invention of new apparatus or of improved technique. The whole of his attention cannot be given to advancement; some must always be spared for the examination, from time to time, of older knowledge.

CHAPTER II

THE FOUNDATION OF CHEMISTRY

As an introduction to this subject, reference must be made to two axioms of fundamental importance.

The first deals with the *Conservation of Matter,* and states that matter cannot be formed or destroyed; any change that may occur is only a conversion of matter of one kind into matter of another.

When coke burns and leaves only a little ash, the carbon has not vanished, but has been converted into an exactly equivalent quantity of a colourless gas which passes away unseen. When a plant grows, it does so only at the expense of an exactly equivalent abstraction of what it needs from the soil and the air; and so with every example that can be quoted.

An analogous principle has been established and is known as the *Conservation of Energy,* according to which energy cannot be destroyed or created; it can only be transformed from one kind into another kind.

Electricity obtained from a battery is exactly equivalent to the chemical changes that have gone on in the battery during its production. The mechanical power obtained from a motor is equivalent to the power put into it in the form of electricity or of petrol, according to the type of machine, diminished by certain known losses in the form of heat, friction, disturbed air, and so on; but the total amount of these various forms of energy obtained is exactly equivalent to that supplied.

Recently these two conceptions have been brought together through the study of free electrons, which constitute part of the fundamental components of the atom (see p. 31), by the recognition of the actual inter-equivalence of matter and energy and their conversion one into the other. This is a very startling conception, and is illustrated by the fact that an increase in the speed of an electron causes it to be endowed, for the time being, with increased mass.

Chemistry is concerned with the composition and change in composition of matter, not with its condition. It is not concerned with such changes as the conduction of electricity or the refraction of light; these lie within the domain of physics, which is concerned with the condition and not the composition of matter. There is, however, a whole section of science which treats, for instance, of the chemical effects caused by electricity, and the variation of refractive index with changes in chemical composition; this is known as physical chemistry.

The inquiry into chemical composition and the laws of chemical change demands a knowledge and a definition of "compounds" and "elements," of "molecules," "atoms," and their components.

The term *compound* explains itself; it is a substance that is made up of two or more different elements. These elements usually lose their own identity in the formation of the more complex substance; in the blue crystals of copper sulphate, for instance, there is no external trace of the copper, sulphur, oxygen, and hydrogen that compose that substance.

The most astonishing substance that I know for possessing properties at complete variance with those of the elements composing it, is the relatively little known compound called phospham. This substance has been used in metal filament lamps for the elimination of oxygen that might have leaked in. It is composed of phosphorus, nitrogen, and hydrogen, and has the formula (see p. 21) of PN_2H. Phosphorus is a very easily oxidised substance; that is, it burns easily and vigorously in air when warmed. Nitrogen is an inert gas; hydrogen also a gas that either burns readily in air or explodes instantly when mixed with it and then ignited. Both of these are known as permanent gases, because it is impossible to compress them so as to form even a liquid under ordinary conditions. Yet phospham, a combination of these three, which might well be expected to be a very unstable if not an explosive substance, is a solid white powder, and so stable that it can only be volatilised at the very high temperature of the blowpipe.

Conversely, these elements can be separated only by chemical action. A moment's consideration will show what this means and in what the difference consists between compounds and mixtures. Compounds can only be decomposed into their component elements by the modification of the energy that exists within the substance of the compound, whereby its constituents are loosened, one from the other. Mixtures can be separated by mechanical or physical means, and there is no better example than the well-known one of iron and sulphur. If powders of these two be mixed together, the iron can be removed by means of a magnet; or the sulphur can be winnowed away by means of a stream of air, or it can be dissolved out by means of carbon disulphide (which does not affect iron) and be recovered by distilling off the solvent.* But if these two substances be heated together, chemical action is started, and the resulting compound, ferrous sulphide, will only yield up its components by chemical treatment.

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* If this be tried, care must be taken against fire and poisoning from the carbon disulphide.

An *element* is a substance that cannot be chemically decomposed into a simpler one. There are over four score of them, and only a very few remain to be discovered. This is known by the lightest of them, hydrogen, having the simplest possible internal composition [one particle of positive electricity—the nucleus—and one of negative (electron)]; and by the heaviest of them being too complex to hold together, so that it breaks up spontaneously and gives rise to radio-active phenomena; in fact, several of the heaviest atoms are in this unstable condition.

This study of radio-activity is one of the most profoundly important investigations before the scientific world, and involves the behaviour of electrons in a partial vacuum and rare emanations from radium, thorium, and the others, the degradation of radium to lead, and the architecture of atomic structure.

A *molecule* is the smallest portion of anything that can exist free and at the same time retain its own identity. Imagine that subdivision were possible again and again until a particle be at last obtained, any further division of which would cause it to be cut in half like an apple; then the molecule will have been reached.

This will be found to be composed of atoms. These atoms may be of different kinds, as would be found in the molecule of copper sulphate or ferrous sulphide, already quoted; or it may consist of one or of several atoms of the same kind, as occurs in the elements.

It is according to the physical behaviour of the molecules towards one another that the substance that they compose is a *gas* (when they are far apart), a *liquid* (when they are much closer), or a *solid* (when they are closer still).

In the gaseous state the molecules are so far apart (and sufficiently far from one another's attractive influence) that they are free to move at their own particular very high speed, though with numerous collisions, throughout the space in which they happen to be.

A highly important place in physical chemistry is occupied by these problems under the general *Kinetic Theory of Gases,* which has been invaluable in helping to explain and to develop the phenomena attending the effects of temperature and pressure.

The chief characteristic in liquids is the development of a surface, the result of a much closer proximity of the molecules, which still show energetic kinetic motion. So close are they that the attraction they exert on one another is much greater sideways and downwards than upwards into the air or into their own vapour. This unbalanced attraction, in all directions except upwards, has given rise to a *surface tension* on the liquid, which has important consequences. The solid state has properties of its own which are familiar to all—retention of shape, brittleness, malleability, and the rest.

The actual sizes and movements of molecules are summarised in the following paragraph (hydrogen is taken as an example):

Diameter: 24 thousand millionths of an inch (24×10^{-9}), or 0·6 millionth of a millimetre. *Number of molecules* (at standard atmospheric pressure and 0°C.): 24 ten million million millions (24×10^{19}) per in^3. *Distance travelled between two collisions:* 4 millionths inch, 10 millionths millimetre (10 $\mu\mu$.). *Collisions per second:* 5 thousand million. *Velocity per second:* 45 thousand cm.; 1,500 ft. *Average spacing in air:* 1 millionth mm. *Average spacing in liquids:* 10 millionth mm.

The figures can be made more comprehensible by the following elaboration (Mellor*):

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* By the courtesy of the Publishers; see Bibliography.

"*First:* A normal human eye, at a distance of 10 inches, can see objects $\frac{1}{250}$ inch in diameter; with a good microscope objects not much smaller than $\frac{1}{50,000}$ inch in diameter can be clearly seen, but this is nearly 5,000 times the magnitude of the molecule of an element. It would take about 40,000,000 molecules touching one another to make a row an inch long. *Second,* If all the molecules in a cubic inch of a gas were laid in a row, touching one another, they would form a line about 35,000,000 miles long, and this line would extend more than 1,000 times round the earth. *Third,* If the gas were magnified on such a scale that a molecule was an inch in diameter, each cubic foot would contain about one molecule, and a molecule would then travel about 100 feet before it collided with another. *Fourth,* It would take about fifty-three years, counting at the rate of three per second, 24 hours a day, to count the number of collisions—5,000,000,000—made by a molecule with its fellows every second. *Fifth,* A molecule travels at the rate of nearly a quarter of a mile per second."

Further, when, in the solid state, the molecules are arranged anyhow, the resulting material has no particular shape; it is *amorphous.* If they are arranged in an orderly fashion, the substance is *crystalline.* A peculiarly excellent example of this, known as "allotropy," is sulphur, which can be obtained in a rubbery amorphous state and in two different crystalline forms.

It must be emphasised—on account of the foolish statement that is heard now and then—that the growth of crystals is no evidence that they are alive. Only the grossest form of superficial analogy can draw any parallel between the behaviour of crystals and the behaviour of living things. Until recently far less was known about the molecular condition of a solid than of the other two states of matter. Now it is possible to ascertain exactly the internal structure of crystals by means of X-rays, and the reasons for the properties that are observed in such compounds are found to result from their internal atomic arrangement—a very beautiful and wonderful advance.

An *atom* is the smallest possible particle of matter. It does not exist free, except in a few cases when the molecule is monotomic, but is united with others of its own kind to form free molecules of the elements or of another kind to form free molecules of compounds.

All atoms have different weights that are natural and specific to them, and for very important reasons they have all been calculated relative to the oxygen atom which has the weight of sixteen. These *atomic weights* having once been determined, it becomes immediately possible to indicate, in the form of symbols, the number of the various atoms that exist in any molecule. There is nothing magical in these expressions; they form only a very simple kind of chemists' shorthand. These *formulæ* are extraordinarily convenient, and it may be said that the chemist, possessing the use of them, was in the same kind of superior position over his predecessors as were the Arabs with their supremely simple mathematical notation (which we have adopted) over the Roman notation, which was so cumbrous that calculation was laborious or impossible.

One example will suffice. Chemical analysis shows that common salt (sodium chloride) has been produced by the union of one atom of sodium and one of chlorine. Written in symbols, this fact is concisely expressed by—

$$\underset{\text{(Sodium)}}{\mathrm{Na}} \quad + \quad \underset{\text{(Chloride)}}{\mathrm{Cl}} \quad = \quad \underset{\text{(Sodium chloride)}}{\mathrm{NaCl}}$$

and the form of the expression is called an *equation*. Further information can be obtained from it. We know that the atomic weights of these elements are sodium 23 and chlorine 35·5,* so that we now have—

$$\begin{array}{ccccc} \mathrm{Na} & + & \mathrm{Cl} & = & \mathrm{NaCl} \\ 23 & & 35{\cdot}5 & & (23+35{\cdot}5=)58{\cdot}5 \end{array}$$

from which we get the useful knowledge that 23 lbs. (or grams or tons) of sodium, uniting with 35·5 lbs. (or grams or tons) of chlorine form exactly 58·5 lbs. (or grams or tons) of sodium chloride.

This is a true statement of the numerical relations between the two substances. Actually the chlorine molecule must be recognised as being diatomic; each molecule contains two atoms, so that the equation becomes:

$$\begin{array}{ccccc} 2\,\mathrm{Na} & + & \mathrm{Cl_2} & = & 2\,\mathrm{NaCl} \\ (2\times 23) & & (2\times 35{\cdot}5) & & (2\times 58{\cdot}5) \end{array}$$

In this form it is more accurate, and the combining proportions remain the same.

An example of a reaction between compounds such as

$$\begin{array}{ccccccc} \mathrm{FeCl_3} & + & 3\,\mathrm{KOH} & = & \mathrm{Fe(OH)_3} & + & 3\mathrm{KCl} \\ \text{(Ferric} & & \text{(Potassium} & & \text{(Ferric} & & \text{(Potassium} \\ \text{chloride)} & & \text{hydroxide)} & & \text{hydroxide)} & & \text{chloride)} \end{array}$$

shows that compounds react with one another in definite proportions, just as the elements do.

Under certain conditions—those of solution in liquids or electrification in gases—atoms (or groups of atoms forming a molecule) can become themselves electrified; they are then called *ions*. These ions, whilst retaining their intrinsic properties, may behave in a manner very different from that which is normal to them.

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* The reason why this is not a whole number will be explained shortly.

This is as far as pure chemistry has been able to go, but physics have carried the subdivision of matter a stage further, and it is found that all the elements consist of the same fundamental components—of particles of positive electricity acting as a central nucleus together with particles of negative electricity (electrons) flying round them. *The difference between the atoms of the elements* consists only of the number of outer electrons in the atom and the equal number of associated free positive charges (there are other positive and negative charges that are bound and therefore obscure) on the central nucleus.

This electrical conception of matter is somewhat difficult to grasp, but there is no doubt of its truth.

Another outcome of atomic research has been the recognition of the fact that many of the elements exist in more than one form : all identical in chemical properties, but differing slightly in atomic weight.* They are called *isotopes*. That is why the atomic weight of chlorine, already referred to, is 35·5 and not an exact whole number; it possesses five isotopes of such weight and present in such proportions as to give the atomic weight found by chemical analysis.

A series of logical deductions has arisen directly from the establishment of the atomic weights, a series of laws stating the conditions according to which chemical reaction—changes in composition—takes place. Parenthetically, it should be pointed out that a scientific law is not an instrument of compulsion, but a concise statement of an established generalisation of unassailable accuracy and truth.

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* For an elaboration of this whole subject, see *The Atom*, by Professor E. N. da C. Andrade.

It is obvious, to begin with, that in any particular chemical compound there are always found the same elements united together in the same proportions, and in the same way. The necessity for these last few words will be seen from the account of organic chemistry, when the same atoms can be combined in different ways to produce different substances.

Then there is the Law of Multiple Production, which states that when two atoms combine with each other in more than one proportion, these different proportions bear a simple ratio to one another.

For instance, iron and sulphur can, according to circumstances, combine to form several substances, of which the formulæ can be written in the symbols with which we are already acquainted, as follows: FeS, Fe_2S_3, FeS_2, Fe_3S_4. If we multiply these formulæ in a simple fashion in order to make them all comparable with the same amount of iron, we get:

$$\begin{aligned} FeS \ &\times 6 = Fe_6S_6 \\ Fe_3S_4 &\times 2 = Fe_6S_8 \\ Fe_2S_3 &\times 3 = Fe_6S_9 \\ FeS_2 \ &\times 6 = Fe_6S_{12} \end{aligned}$$

where the proportion of sulphur varies according to simple whole numbers—a simple and not a complicated ratio, because we are dealing with separate whole atoms and not fractions of an atom.

This is one of the innumerable examples that can be quoted of *valency*—the capacity by which one atom of one element is enabled to combine with one or more other atoms. The single atom of iron has two and three combining bonds; sulphur has two, four, and six, according to circumstances; and this is why these complicated iron sulphides can exist. Carbon has almost invariably four such valency bonds, the importance of which will be seen later.

Gases, being in a different condition from solids, have analogous but different laws of their own. A closely similar law to the above enunciates that gases react in volumes that bear a simple ratio to one another and to the volume of the gaseous product of the reaction.

Less immediately obvious but equally true is the law that equal volumes of all gases, at the same temperature and pressure, contain the same number of molecules.

There are other laws besides these, but enough have been cited to indicate the nature of the fundamental principles that underlie established chemical behaviour and chemical change, directly resulting from the fundamental theory of the existence of atoms.

CHAPTER III

DEVELOPMENT OF CHEMISTRY FROM ALCHEMY

THE origin of the word "chemeia," from which "chemistry" is derived, is not clear; but its early association with the art of the transmutation of the elements, which shows evidence of Persian, Chaldean and Hebrew, Egyptian and Greek sources, suggests that alchemy began its development in Alexandria. About 300 B.C. this city was a famous centre of learning; it had a library of about half a million manuscripts and possessed for a time a real university.

Later, during the first to third centuries A.D., the mystical element was introduced, and alchemy became a secret cult. Subsequent Christian hostility to the pagan philosophies led to the downfall and destruction of intellectual Alexandria. The scattering of disciples and the occupation of men's minds with the rise of the Christian Church left no opportunity or encouragement for scientific development; and when attention was again paid to it, in Europe, it grew up only as an appanage to religious thought.

However, by good fortune the Alexandrine teachings were not lost. The scattered scholars found refuge in Persia, keeping alive the sacred fire of knowledge (as distinct from speculation); and when the great Arabian supremacy swept along the Mediterranean coast and penetrated into Europe, scientific knowledge rapidly developed and became disseminated in the form of Latin translations.

It is interesting to note this Arabian influence, which is preserved in some of our words like flies in amber—*al*-chemy, *al*-kali, *al*-cohol, *al*-gebra, and the like.

" Alchemy had its origin in the attempt to apply, in a certain manner, the principles of mysticism to things of the physical plane."

It sought to prove the unity of the cosmos with God at its head, and the splendour of man, composite of body, soul, and spirit. The ultimate means of doing this was through the Philosopher's Stone (with which is intimately associated the Elixir of Life), an all-powerful source of wisdom, health, and wealth, which at the same time symbolised Jesus Christ. Therefore, the prime object of the alchemists was the search for this stone. The earliest serious practitioners were monks, so that the religious habit of thought penetrated and imbued this proto-scientific work.

The fatal error—an error which is found in much non-scientific thought to-day—was the reliance, for the interpretation of ideas and observations, on analogy. The uselessness of such a weapon lies in its superficiality. It deals with the surface appearance of things, their " at-first-glance " similarity, their empirical associations. Satisfaction with such chance similarities, as a means of interpretation, precludes any possibility of seeking the deeper and more fundamental meaning of the discoveries that were made.

There was considered to be an analogy between spirit and matter. The metals were thought to grow in the earth under the influence of a particular planet, analogously to plants, the most perfect growth being gold. This, therefore, was analogous to man, the most perfect living thing; the transmutation of metals (by the Philosopher's Stone) was analogous to the progress towards perfection of spiritual man. Such ideas, linked together in this fashion, could all be solved by one key, and this key, again the Philosopher's Stone, was sought through material means—namely, proto-chemistry, as we might call it from this distance in time.

The writings of the alchemists are very difficult to understand, partly on account of the intimate associations of mysticism with fact, partly on account of the allegorical method of recording processes, the picture writing that they adopted where we to-day would use formulæ and equations, and the unusual meanings implied by ordinary words. There can be no doubt that obscure language was purposely employed so as to preserve their discoveries from being stolen by their fellow-workers, or from being understood—or misunderstood—by the common herd. Still greater trouble is caused by the adoption by the alchemists of the theories of the Greek philosophers. To these ideas those of the Hindus bore much similarity, but their influence on European thought was slight.

The Greek contribution was of far less intrinsic value than the ideas of the alchemists themselves, because they were based on little definite experiment. They considered that some single form of matter appeared under the different elements of earth, air, fire, water, and "ether." These then gave rise to the properties of dryness, moisture, warmth, and coldness. Substances that were cold and moist possessed these properties because they contained the element of liquidness. And with this mixture of notions were interwoven the alchemists' own further views that all metals consisted of sulphur and mercury, terms which probably had not the meanings that we give them nowadays; perhaps they represented the principles of combustibility and colour on the one hand and general metallic properties on the other.

Credit has been claimed for the alchemists on the ground that sometimes their ideas were somewhat closely similar to those of to-day, and that our latest theories and practices can be connected with those earlier ones. Personally, I disagree with this; I think that no praise is merited, beyond that due to remarkable perseverance and isolated practical achievement, when vaguely or even clearly correct views are the erratic result of wrong thinking. A few isolated accuracies amidst a sea of falsities and surrounded by a fog of wrong-headedness are not impressive, because the value of the accuracy of a scientific fact is not merely for its own sake, but also for the accuracy that is reflected on to all associated facts. Chemistry only became chemistry when this wrong-headedness gave way to correct thinking, whereby isolated facts became intimately connected with one another and with all subsequent ones. All that can be said in favour of the theoretical ideas of the alchemists is that some sort of theory by which to work is better than none.

A much more serious claim for respect to be paid to the alchemists could be based on the fact that they really did experiment; they carried out practical work and made discoveries. That they did not make even greater advance was doubtless due, in part, to their having to make every bit of their apparatus themselves, which must have absorbed a large portion of their time. No wonder that, after long periods of preparation, when an experiment broke down, the failure was ascribed to the direct intervention of the devil!

Practical alchemy appears to have developed steadily in a technical direction as a phase additional to that of the search for the Philosopher's Stone and similar problems. Passage of time and an increased number of workers could only result in an ever-increasing accumulation of facts.

This went on till the time of the tempestuous Paracelsus of the sixteenth century, who is important for having given alchemy a definitely medical trend, based on his view that illness was the result of disturbed bodily chemistry. This acute idea, however, was fully vitiated by the current sulphur-mercury-salt theory of constitution and "analogistic" forms of argument. Thus began the second tendency for chemistry to develop and later to separate completely from alchemy.

In the work of van Helmont (sixteenth to seventeenth century) is seen an increasing tendency towards real chemistry, though of medical aspect. He invented the word "gas." However, his work also remained alchemical and, in thought, fantastic.

Glauber, too, whose name is still a household word, worked at applied chemistry. More and more rapidly was the "true word" coming to light, and all the more quickly as alchemy was fast becoming discredited by the amount of trickery that had to be indulged in to bring about the promised transformations.

A sort of transition phase between alchemy and modern chemistry was the development of the Phlogiston Theory, which began in the late seventeenth century. This theory, which delayed real progress for some time, enunciated that a metal was a compound of an oxide + phlogiston (the active principle of combustibility). It was exploded when Lavoisier, the French scientist (late eighteenth century) weighed and measured his materials before and after reaction. Then it was found that phlogiston must have negative weight, which led to a reversal of views and the immediate progress of theory. The leap forward that chemistry took dated from the time when mathematical calculations began to be applied to it.

The birth of "pure chemistry" took place with the advent of the Hon. Robert Boyle (mid-seventeenth century), who studied chemistry for its own sake with a penetrating and cultured mind. His work had high value, not only for its own sake, but for the independent and critical attitude he took towards current ideas. Speed of progress was still further increased by the enunciation by Dalton (early nineteenth century) of his Atomic Theory. The idea was not new; Aristotle and others throughout the ages had formulated such ideas. But the supreme value and driving force of Dalton's theory lay in its experimental basis of weight and measurement. Later experience has required important modifications of it, but Dalton is just as much the father of modern atomic chemistry as Darwin is of the modern position of evolution.

Dalton considered that the simplest form of matter—an element—could be subdivided down to the smallest possible particle that was still able to retain its distinctive characteristic. This he called an atom because it could not be divided further; he considered it to be indestructible, to vary from one element to another both in nature and in weight, but to be similar to all its fellows in each particular element. It was the union of the different atoms with one another that gave rise to the molecules of all the various complex substances that were known.

On these basic ideas were founded and developed the various fundamental laws to which reference has already been made. In determining the relative weights of his atoms, Dalton took hydrogen as his unit because it was the lightest element known. For this same reason, Prout stated in his hypothesis (1815) that hydrogen was the actual fundamental material from which all other elements were formed. Such an idea was inevitable, on the one hand because the alchemists' craving for a unity of the cosmos was too recent to have lost all its force, and on the other because the mind of man is continually seeking for explanation and simplification of confusion to orderliness, and hydrogen was the obvious unit to adopt.

We now know that this was a big step towards the truth, for hydrogen is the simplest combination of the two types of particles of electricity from which all matter is built.

Dalton's postulations were only approximately true. Many atomic weights were not whole numbers, but varied from these by small fractions; the worst case was that of chlorine, already noted, with an atomic weight of 35·45. An improvement of convenience was made in recent years by changing the unit from hydrogen = 1 to oxygen = 16, whereby hydrogen becomes 1·008.

The well-known and utterly fallacious saying that "exceptions prove the rule"—and how many of our well-known sayings are fallacious!—might well be replaced by the simple truth: "Exceptions weaken the rule." Just as true is "Explanations of exceptions strengthen the rule," and as a result of a still developing series of researches, which may be counted among the most brilliant of all that have graced man's intellectual progress, these small fractions are being accounted for, with a penetrating understanding that is unifying the widest regions of human thought.

It would carry us too far afield to go into this matter,* so that bare mention can only be made of a few of the men and means that have been concerned in its achievement—Sir William Crookes, Röntgen, Sir J. J. Thomson, the Curies, Sir William Ramsay, Sir Ernest Rutherford, Moseley, Bohr, Fowler, Eddington; who variously employed vacuum tubes, X-rays, radio-active substances, the spectroscope; whose researches range from the interior of the atom to the life histories of the stars.

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* See *The Atom*, by Professor E. N. da C. Andrade, in this series.

This last remark might be considered to be an acknowledgment of the discovery of the unifying principle that the alchemists searched for. Superficially it would seem to be so, but actually the mental equipments of the moderns and the medievals were so different that one might say that the fish at the bottom of the sea and the gull in the air are companions in progress only because they occasionally move by chance towards the same compass-point.

CHAPTER IV

THE NATURE AND DIVISIONS OF CHEMISTRY

Chemistry used to be considered as consisting of two kinds—inorganic and organic—the former being concerned with all sorts of non-living matter, and the latter with living things and their products. It was thought that substances formed in contact with life differed in their nature and behaviour from substances that were obtained from the earth or from the air. This differentiation was proved to be false when Wohler, in 1828, showed that the typically organic substance urea could be produced from inorganic materials in his laboratory.

The division has, however, persisted because it incidentally segregates as " organic chemistry " the chemical behaviour of almost all the compounds of carbon, an element of which one peculiar property has made possible the animate world as we know it.

Inorganic Chemistry covers the activities, among themselves, of all the remaining elements, of which there are over four score. They are of widely differing nature—solids, liquids, and gases; metals, metalloids, and non-metals; substances that are highly reactive and those that are completely indifferent; acids, neutral substances, and alkalies, coloured and colourless, all behaving according to the rigid limitations of their constitution and the laws of nature, and acting in varied but invariable ways.

The number of compounds they form has never even been estimated, but it is certainly only a fraction of the number of organic compounds. They may consist of true compounds like any of those that have been mentioned, or they may form definite but loose associations like some of the amalgams (alloys of mercury with other metals). Some may contain so much water combined in their crystals, as does washing soda, that the water evaporates more quickly than it is resupplied from the air, so that the well-formed crystals break up to a white powder. Others, like quartz and the noble metals (a phrasal legacy from the alchemists) may remain unaltered for indefinitely long periods of time. Their variety is great and wonderful.

A specialised section of this division is *mineralogical* chemistry, a branch that connects chemistry with geology. It is concerned with the composition of rocks, minerals, and ores, and with the conditions of their formation and change under the enormous temperatures and pressures that obtain within the earth. An interesting and most peculiar agent for such activities is water, when under such tremendous pressures that, however high the temperature may be it can never become converted into steam. In these conditions it acquires a relatively high solvent power for what ordinarily is insoluble, and during prolonged geographical periods profound and curious changes can take place.

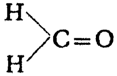
The majority of mineral substances, apart from most ores, consist of metallic oxides (metals combined with oxygen) combined with silica, the oxide of silicon (sand consists of silica). The felspars and most gem stones are examples of this. Very frequently these silicates are extremely complex, and it may be of high significance that silica is classed chemically with carbon (see " Organic Chemistry "), which also can give rise to a series of extremely complex compounds.

Organic Chemistry has been, for years past, the chemist's chief playground; there appears to be no end to it. When I was a student it was stated that the hundred thousandth organic compound had been made; recently the advent of the two hundred thousandth was announced.

These bounding numbers result primarily from that peculiar property of carbon which has been hinted at already—the capacity of the carbon atom to combine with large numbers of other carbon atoms. Not only are these united to one another in straight lines or chains—sixty in a line are known—but also in the most complex of patterns; so that, for example, although only ten carbon atoms may be concerned in the structure of a molecule, those ten atoms may be arranged in several different ways and so give rise to compounds with as many different series of chemical and physical properties.

These compounds are divided into two big groups depending on the general nature of the arrangement of the carbon atoms, whether they consist of " chains " or " rings."

Chain compounds have their carbon atoms arranged in a line, with or without branching side chains. Ring compounds consist of simple or complicated association of closed rings of three, four, five, or six atoms of carbon; the number of the members of the compounds of the six-atom ring is by far the largest, and the shape of the ring is a hexagon.

Whatever be their arrangement, the carbon atoms are copiously supplied with hydrogen atoms, and may also be joined to a less number of oxygen, nitrogen, and sulphur atoms, and to a few other elements besides. These may be combined as atoms or united to the carbon atoms in the form of groups, such as $-SO_3H$ or $-NH_2$. And throughout the enormous complexity of this section of chemistry, with the rarest exceptions, carbon keeps rigidly to its valency of four—its capacity to combine variously with four single valency atoms or two two-valency atoms, and so on, examples being CH_4 (marsh gas) or $H{-}C{\equiv}N$ (prussic acid) or  $\begin{matrix}H\diagdown\\ \quad C=O\\ H\diagup\end{matrix}$ (formaldehyde).

The sources of the enormous number of organic compounds—like the inorganic ones also—are in or on the earth as well as in the laboratory.

Every scrap of matter in the world is an element or a chemical compound of a specific nature. Very many of these compounds have been imitated in the laboratory, and often by methods quite different from those that produced them naturally; some still defy such imitation. These substances, by whatever means they have been obtained, are used as starting-points for the preparation of still more compounds which have never occurred in nature, but which are studied, with the others, for their possible value to man, or intrinsic interest, or, in their own turn, as further starting-points for the synthesis of still more compounds that are ever of possible interest and value.

In order to focus the mind, even if by necessity cursorily, mention must be made of a few of the naturally occurring substances of interest to the organic chemist as apart from the technical man and the manufacturer.

Most of these come from the vegetable world, on account of the greater magnitude of the source, the greater diversity and concentration of products, and greater availability of raw material.

There are the sugars of which several different kinds are found in plants. A considerable number of new ones have been manufactured in the laboratory by violent chemical means, very different from Nature's gentle but persistent methods. These methods have, however, actually begun to be imitated in the laboratory, in a very beautiful piece of research.

Closely related are the starches and cellulose, all known as "carbohydrates" because they consist of carbon, together with hydrogen and oxygen that are in the same proportion as they are in water.

The alkaloids are very complex substances that contain nitrogen, extremely active physiologically and identifiable in extraordinarily dilute solutions.

The proteins are the most complex of all chemical substances and form the material that is contained in all the microscopic cells of which animal and vegetable organisms are built up. It is here that one of the portals to the secret of life may be found.

Among the compounds simpler than these are the acids to be found in fruits, the oils, some comparable to animal fats, and others constituting the scents of flowers and fruits and trees. There are also the various gums and rubbers, which, again, are of complicated structure.

A few anciently formed organic compounds occur naturally, such as certain resins and petroleum. Although the latter is properly classified by the geologists as a mineral—even its popular name of "mineral oil" is an accurate one—it was classed by the chemist as an organic compound on account of the characteristic carbon skeleton of its numerous constituents, long before he suspected the living agency of bacteria to have contributed to its formation from fish and lower forms of life.

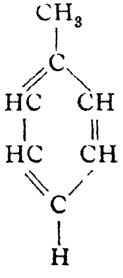
The tar resulting from the destructive distillation of coal contains substances representing half the realm of organic chemistry, and may possess very interesting individual characteristics.

It is curious that although the molecular structure of organic compounds can be so complicated, the general nature of the chemical reactions giving rise to that complexity is simple, much simpler than many of the inorganic reactions.

If an oxygen atom in one molecule combines with two hydrogen atoms in another (or sometimes even in the same), water is formed and separates, and a new single compound is formed by the union of the two remaining fragments of molecules. Or, in the same kind of way, hydrochloric acid is driven off from between two different molecules, the residues of which then unite with one another. Such changes as these are also found in inorganic chemistry, but they have not such far-reaching and complicated results as occur in organic chemistry. Many changes occur, too, by several molecules of the same kind collapsing into one another, with neither loss nor gain, whereby a heavier molecule of different properties is formed.

It has been possible to follow the increasing elaboration of organic compounds by a corresponding elaboration of the method of their representation by formulæ and equations.

The simple way of representing toluene, for instance (a sort of elder brother of coal-tar benzene), is C_7H_8. More information is given by writing it in the form $C_6H_5CH_3$, which gives an indication of the groups of atoms present. More still is seen in the " structural " formula—



where the arrangement of the carbon atoms (with their valency of four bonds) consists, as a foundation, of the hexagonal "benzene ring," and the position of the hydrogen atoms is clearly shown.

In many cases even this method, though valuable, is imperfect, because it shows the molecule as a flat two-dimensional thing, whereas in many cases a three-dimensional formula gives still more information.

Thus, from the use of letters and numbers, there has been developed something that almost approximates to picture writing.

A link between chemistry and biology is formed by *biochemistry*. This is a branch of the subject that has become highly specialised to deal with the chemical problems and principles underlying the existence and maintenance of life and all its functions. Not only is it a subject of the greatest complexity, but the quantities of material that are available are often very small, so that a particular technique has been developed.

PHYSICAL CHEMISTRY is the third major division of chemistry, and covers the territories that stretch along either side of the border line between chemistry and physics.

This branch of chemistry is another example of the rapidity of progress that results from the application of mathematics to any subject. Calculation demands an orderliness and a precision that, to the greatest degree, facilitates the discovery of underlying laws and principles; it saves an immense amount of time in experimenting; it is an invaluable theoretical touchstone for the accuracy of experimental work.

Physical chemistry deals with the physical properties of substances, such as change of boiling-point with pressure; of solubility with temperature; the proportions in which a substance is distributed between two others with which it can combine or dissolve simultaneously; also with the differences of physical properties resulting from variation of chemical composition, and of the chemical changes that occur through the agency of physical forces. Of the first, an example is found in the differing capacity for bending beams of light, that is shown by glasses of differing chemical composition; of the second, the changes caused in a solution of copper sulphate by the passage through it of a current of electricity, as already quoted.

In this section, too, are included the study of the conditions and the speed of chemical action, depending on the relative proportions of the reacting substances and on temperature; the heat evolved or absorbed when reaction occurs, and the extraordinary changes that happen to both when one substance is dissolved in another one; and the conditions for their separation by evaporation, crystallisation, and so on; the action of light in promoting chemical change; and a host of other most important problems.

In this section, too, is included those wonderful investigations into radium and its radio-active relatives. On the physico-chemical side—omitting the more purely physical researches into atomic constitution—one result that has been established is that the age of the world is far greater than was previously considered, to the great relief of the biologists, who wanted more time for evolution to take place in than was previously allotted.

It is very remarkable how the recent development of physical means for examining the inner constitution of the atom and of the atomic structure of crystals by X-rays has led to the substantiation by the physicist of the theoretical deductions of the chemist, who could only work, as it were, from the outside. Most startling is the establishment of a hexagonal atomic structure of the molecule of benzene and its related compounds, which the chemist has long postulated from purely chemical evidence.

A very interesting extension of this branch of chemistry is the link with *astronomy*, through the spectroscope. A spectrum is a direct effect caused by the movement of molecules and of electrons; so that the spectra of the heavenly bodies, associated with research in the laboratory, are made to yield an amazing amount of information that is invaluable to astronomical research. Thus problems concerning the most stupendous magnitudes are being solved by the study of the minutest of discovered entities.

CHAPTER V

THE APPLICATION OF CHEMISTRY TO HUMAN AFFAIRS

It should be needless to state that the development of science as a whole and chemistry in particular is so difficult and arduous that only the fully trained are fit to attempt it; trained not only by the accumulation of knowledge and in the method of scientific thought, but also in the performance of experiments in the laboratory with delicate and complex apparatus. Yet too often one hears of and reads the intellectual results of minds, active enough to demand most vigorous exercise, but too ill-informed and unorganised to produce results of value.

Therefore, from among the divisions into which the application of chemistry may be divided, Professional Chemistry is put first, as consideration of it must include the training that a practitioner must undergo.

This examination of the PROFESSION OF CHEMISTRY includes both the attitude of the individual towards the science and the demands made by the science on the individual.

The choice of chemistry as a profession is usually made by a boy on the basis of his acquaintance with it at school or as a hobby. The high importance of chemistry during the Great War acted as an advertisement so marked that, coupled with subsequent encouragement from the Government, a large number of students entered the universities and technical colleges. As a result, at the moment of writing, the demand for the services of chemists is such as to require that boys shall take up chemistry only if their bent is so strong that they cannot be kept away from it; a general liking or choice arrived at merely by the exclusion of other occupations is strongly to be discouraged.

It is very undesirable for an ill-educated individual to take up chemistry with the expectation of going far with it; it is almost impossible for him to do justice to himself, to the money spent on him, and to his teachers. A sound general education is essential; firstly, because the mental machine becomes thereby partly trained and forms a good basis for further and higher development; and, secondly, because every scrap of knowledge and cultural attainment may be of value, directly or indirectly, at any moment, and may serve as the beginning of new ideas and of scientific and (of less importance) of personal advancement.

Such is the ubiquity of chemistry and the intimate and ultimate ramifications of its associations that it is not sufficient only to learn as much as is possible of this branch of science. It is essential that a considerable acquaintance be made of most of the associated sciences of physics, mathematics, mechanics, geology, and biology, as a kind of background or help to the understanding of chemistry. I do not mean to imply that chemistry is superior to all other sciences and that these are only its handmaidens—comparison of the sciences on such a basis is always pernicious—but I do mean that whatever science is studied as a main subject, a knowledge of the others is necessary for a fuller understanding and a more richly stored mind.

As the word " training " is a little vague, it should be explained and made more definite.

Apart from the actual accumulation of precise knowledge, by the time a chemist—or any other practical scientist—has finished his courses he will have acquired an invaluable ability for orderly thought, to be paralleled, perhaps, only in the case of the lawyer.

This trained method of thinking he can apply to every problem of life as well as to his science; for life is not built up of water-tight compartments, but is a complex unity. To learn justice and kindliness over the week-end and not to apply them for the remainder of the week is repugnant to the true scientific mind.

In his work this orderly mental habit directs and controls his thoughts, and projects his imagination forward in the interpretation of his results and in devising fresh experiments for further advance. He will also have acquired valuable manual skill by the construction and manipulation of his apparatus.

He will have learned to look upon his work and that of others with an unemotional, impartial, and detached criticism, and to develop a patience and a restraint that should be ever active on all occasions. Most certainly he will have learned, and most profoundly, how to "play the game." This attitude of the scientist towards his work and the world is not an ideal too perfect for human achievement. It is usually attained, and any falling off is more likely to be due to the backwardness of the world's conditions and not of his feelings towards it.

It thus becomes clear why a chemist must have a good general education, a broad scientific training, a more detailed chemical knowledge, and as complete a one as possible of the particular section he takes up.

It is almost imperative, too, for him to belong to one or two of the chemical societies, and to keep in touch with current scientific knowledge through the particular weekly and monthly journals concerned with his interests.

In truth, the training of a chemist is never ended; he is a student all his life, and thereby attains incidentally but inevitably an ever-broadening humanity. The real scientific spirit is never obstinate or arrogant; the true appreciation of the wonders of Nature develops a humble rather than a proud spirit. The immensity of knowledge in view is nothing to that which is to come. The realisation of this is enough to preserve any mind from conceit.

It is highly desirable for his own sake, and for the sake of his ultimate employer, that the chemist should complete his training and become qualified by a University degree " and/or " the Associateship and Fellowship of the Institute of Chemistry.

The section of chemistry that the individual studies depends partly on opportunity, but success in it, to a great extent, depends on the " make-up " of his character, whether as regards his adaptability, or his quickness of mind, or his personality.

This is, perhaps, most clearly seen in the profession of *teaching*, which is very complex and exacting in its requirements. Here is required not only wide chemical knowledge, clearly docketed in the mind, but also a power of vivid exposition, of the exercise of authority, of developing the best that is in each individual student, and of exercising that diplomacy amongst the other teachers and professors that circumstances not infrequently require.

Nowadays teaching is, so far as possible, combined with opportunities for the carrying out and directing of original research, and the *research chemist* may ultimately achieve one of the highest types of mentality.

Analytical Chemistry is of fundamental importance, as advance can only be made by ascertaining the composition of the substance employed or newly discovered; it must be constantly practised in all research laboratories.

This type of work has become specialised in a professional direction, the practitioner of which is the *consulting chemist*. He applies his chemical knowledge to analysis in connection with the raw materials and current products of factories in order to safeguard, by independent examination, the quality of the output. He may be consulted regarding future industrial developments, the scientific value of chemical patents, and any other questions of a chemical nature. As may be expected, there is usually a tendency towards specialisation in most laboratories of this nature.

Those analysts who have made a particular study of food and of drugs may be appointed *public analysts* for the examination of samples, taken by duly authorised officials, for the protection of the public health and pocket against the possible errors or falsifications of the manufacturer and retailer.

The chemist in the service of *industrial* interests is required to keep a watch on the nature and quality of the raw materials coming into the factory—including fuel and water supplies—on the stages of manufacture, and on the finished products going out. In this he acts as analyst. As *research* chemist he has to effect improvements in the factory's processes and to invent or investigate new ones. He may be called upon to apply his chemical knowledge to the control of plant, or of the works, or, together with others, of the company. This last activity—the chemist as director—is much less the custom in this country than in others that have fuller and more extended faith in chemistry as a national asset; but in this respect the outlook is improving.

It is out of the recognition of the technical value of the chemist when in association with the engineer that the new profession of *chemical engineer* has developed. In the design and working of plant he combines in himself the necessary specialised knowledge of both professions. Abroad the value of this type of scientist has been recognised for a considerable time, but in our case it was the Great War that made evident the high importance of his work by the revelation that we possessed so few of this type.

Finally, there is the *pharmaceutical chemist,* who is concerned, primarily, with the dispensing, composition, doses, and effects of medicines and drugs; he must be acquainted with the laws governing his relations to the public, and must have acquaintance with retail shop practice.

Although his training is as prolonged as in any other branch, some of his duties are being taken over, more and more, by the chemical manufacturer, leaving his retail activities in greater prominence. It is this (combined with the increasing tendency to sell goods other than those immediately connected with the concern of health) that has aggravated the dislike of the more purely professional chemist to being confused, in the public mind, with the dispensing chemist.* There are, however, great legal difficulties in making a definite distinction between the "chemist" and the "druggist," as is done in most foreign countries.

It must be remembered that in all contact with the industrial side of chemistry any business knowledge or experience may be of great service to advancement.

Applied Chemistry means, as its name indicates, the intentional application of chemical knowledge to any particular purpose, so that it covers the whole host of uses to which chemistry is being put every day, everywhere, at the service of humanity in the vast variety of its requirements and in the numberless points of contact and association with other sciences.

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* In the same way the public does not discriminate between the designers of bridges and engine-drivers: both are "engineers."

Thus the designation is a wide one and includes "industrial chemistry" in its ambit. It is, I think, preferable to separate them, limiting "industrial chemistry" to mean the employment of chemistry for industrial purposes, and "applied chemistry" to cover those immediately useful activities that are not of an industrial nature. Doubtless the division is often a narrow one, but, taken broadly, the distinction is useful.

Applied chemistry, then, is to be exemplified by the study and prevention of the attack of city atmosphere on building stones, by the preparation for exposure in museums of newly discovered and damaged objects, and by all the problems associated with cookery.

Industrial Chemistry is the spinal column of a manufacturing nation, and if this country is to escape wilting in face of continuous industrial progress elsewhere, it must ever be making increased efforts to acquire and retain a foremost position amongst those nations that have less inertia and a greater confidence in science.

The situation in this country has improved since the war by the activities of the Department of Industrial and Scientific Research, but even now we can hardly claim that British industry possesses the scientific spirit that is to be found in the most progressive countries.

So intimately is chemistry bound up with a nation's economic condition that, as was pointed out long ago, this may be measured by the amount of sulphuric acid that is consumed in industry, a statement that is based on the very large number of chemical processes in which this acid takes part. The consumption of coal has also been proposed as a similar kind of measure, but nowadays, with the increasing use of oil, this is not so clearly significant.

Vast as is its domain, the area covered by industrial chemistry is more precise than that of the last section. A quick survey of this reveals at once the tremendous responsibilities for the support of modern civilisation that are borne by the chemist and the engineer. The sudden removal of either would instantly throw the world into complete chaos, and if it ever emerged it would be found to have lost a thousand years of the most rapid progress that has ever been made.

The chief headings into which industrial chemistry may conveniently be divided may be briefly summarised in the following way:

The *metal industries* deal with the smelting of ores and the properties of the resulting metals and their alloys which make possible the development, for instance, in types of machinery, engines, cars, typewriters, electric lamps. The advent of the explosion turbine has been delayed until an alloy could be found to stand the stresses and temperatures involved.

The *fuel industries* comprise solids, such as coal, wood, and peat; liquids, such as petroleum and light coal tar oils; gases, such as coal gas, water gas, and, in America and Canada, natural gas. With the production of coal gas is inevitably associated the production of tar, and the preparation of this material for commerce is a great industry in itself. Huge as is the amount of work that the chemist has done, he is still far from knowing completely the composition of these raw materials and their products, and from understanding the changes that go on during distillation.

The *heavy chemical industries* produce sulphuric, hydrochloric, and nitric acids, alkalies such as soda, salts such as the combinations of these two sets of materials, and many others, as well as bleaching powder and fertilisers. These are dealt with in large quantities and handled in the big way of general merchandise.

The *fine chemical industry*, on the other hand, is relatively small in output, but it is of importance because valuable medical preparations, research chemicals, and highly specialised substances of great purity are prepared and made available.

The *silicate industries*, too, have complex ramifications. Purified china clay itself finds widespread and unexpected uses; but the production of glasses for many purposes, ceramics, building materials, cements, and furnace linings that have to survive prolonged and very high temperatures in repeated heating and cooling, have all presented peculiar problems of a most varied kind that the chemist has continually to meet and solve.

The *paint and varnish industries* play a great part in human existence, not only for that embellishment and beautification of our lives that is essential for our mental (and therefore bodily) health, but for the protection of structures both on land and on sea. In the main, paints consist of inorganic solid matter very finely divided and suspended in an oil that dries after application. Varnishes are composed of a weather-resisting resin-like substance dissolved in a liquid that evaporates and leaves behind a thin shiny coating. There are many elaborations of these two simple principles.

Disinfectants and antiseptics, with which may be associated *insecticides* and their associates, may not, perhaps, constitute so well-defined an industry as the others, but are of deep importance to our health and to the leather industry.

The *organic chemical industries* are divided from the rest for the same artificial reasons of convenience as occurred in pure chemistry, but the distinction is not so well defined.

The *dye, explosive, and photographic industries* are usually considered together, as the manipulations of one or the other can be modified for the production of the third. They depend for their raw materials mainly on coal tar products and cellulose (preferably cotton) and on glycerine (obtained from the manufacture of soap). It is the "coal tar intermediates" that are so closely related to some of the most valuable explosives.

Oils, fats, and waxes are of far-reaching importance to us. According to their source, composition, and properties, they enter into the manufacture of food, raw material for soap manufacture, vehicles for paints and varnishes, illumination, medicine, furniture, and boot polishes. In many cases a liquid oil can be converted into a solid by the action of hydrogen in the presence of finely divided nickel, a most remarkable process that will be referred to again.

Sugar and starch are usually considered together because they are related in their chemical structure and because starch can be converted into glucose, which is one of the sugars.

Sugars are used for sweetening and for fermentation into alcohol, a change which can occur normally within the human body. Starch is used as a food, as an adhesive, and for the formation of the gum dextrine.

The *paper industry* is based on cellulose of some form, usually wood pulp and esparto grass and, less frequently in these days, of linen and cotton rags. Many mineral admixtures are made to produce papers for specific purposes.

Soap-making is an enormous industry, and requires oils and fats or rosins and alkali for its raw materials, and yields glycerine as a by-product. According to the nature of the materials employed, there result soaps suitable for toilet purposes, domestic use, scouring wool and cleaning textiles, and paper-making. And according to additions that are made, the soaps possess properties of increased detergent action, disinfection, and bleaching.

Great industries, too, have been built up that have enriched the available amenities of life through the provision of *rubber, gums,* and *resins, leather and glue,* and the huge volume of *food products.* About the latter great controversy is proceeding between the manufacturers on the one hand, who produce seasonal delicacies all the year round, and overseas products to supplement our own in bulk and kind, and on the other hand chemical and medical authorities who disapprove of the presence of preservatives and deodorants and of impurities due to occasional faulty methods. Current legislation indicates that the scientific watchdogs are getting their way, and recently there has been a strong line taken as to the value of food containing not only its ordinary constituents in an unchanged condition, but also its natural amount of the immediate result—whatever it may be—of irradiation by light.

It has been stated earlier that it is essential for the chemist to have a sound grounding in, if not deep knowledge of, the principles of other sciences. This is nowhere more important than for the industrial chemist, whose work is in immediate contact with physics, particularly electricity, and more especially with electro-chemical and electro-thermal processes, and with engineering, and whose results are to be converted automatically, directly or indirectly, into money.

It is an old quip that the industrial chemist does things and the scientific chemist tells him how he has done them. This may be true to the point of explanation, but on the basis of the knowledge acquired for this explanation the scientist goes ahead and is able to make improvements and developments for which the industrial chemist is grateful.

The other mode of progress is for the scientific chemist to develop, by association with the industrialist, the discoveries made in the laboratory, and here there is a deep debt owing from industry and the country at large to the scientist. That debt is not always adequately liquidated, partly as a result of the completely different natures and points of view possessed by the scientist and the industrialist, and partly because the enjoyment the scientist finds in his work is—quite unfairly—looked on as part payment. " You will never be well paid for doing what you like," was said to me when I was starting—a terrible comment on man's position in the universe.

Analytical Chemistry consists of changes brought about with the object of discovering the composition of a substance or mixture of substances; that is, the proportion in which the atoms exist in the molecule of each substance and the quantity of each substance in the mixture.

In such work three degrees of accuracy are demanded, depending on the requirements and nature of the operation. Sometimes it is only necessary to know within an appreciable limit of accuracy whether a mixture is correctly constituted. Ordinarily, accuracy to a small fraction of 1 per cent. is required, the results being obtained with all possible correctness under normal conditions. This may have to be modified for the sake of speed of working, and the attainment of the balance between these two requirements—accuracy and time—constitutes one of the trials of a technical laboratory. Finally, there is " atomic weight accuracy," when the utmost care and precaution are taken to obtain results as accurate as it is possible for them to be.

The subject can be divided in several ways for the sake of convenience of consideration, but in practice there need be no such separation. Analysis may be carried out qualitatively or quantitatively—for the sake of ascertaining the nature of the substances or groups of atoms that are present, or for determining the proportions in which these may occur.

Qualitative analysis of an unknown substance (which may be a mixture) is carried out according to a scheme of gradual elimination from a solution of the material of one group of substances after another in an insoluble form, and the examination in detail of each group thus separated. This is the " wet way "; there is also a " dry way," depending on the behaviour of the material to heat under prescribed conditions.

Quantitative analysis can only be applied to a material of a composition known from such an examination as the above or from the general conditions in which the sample was obtained.

In the *gravimetric* method the procedure may resemble the "wet" qualitative examination in which careful weighing of the dried substances is made at every stage of their separation.

Instead of separating the substance to be estimated by chemical methods, electro-chemical means may be used in a restricted number of cases. An electric current is passed through the solution and the substance, usually an element, is removed as an "electro-plating" to be weighed or as a gas to be further examined.

Volumetric analysis depends on measuring the exact volume of a solution of known strength that is required to bring about a desired result. The attainment of this result is usually shown by some kind of indicator, a substance that is added which changes colour when the smallest excess of one solution, beyond what is necessary for exact chemical equivalence, has been added to the other. Sometimes this equivalence is ascertained by measuring changes of electrical properties.

The results obtained by this method are not so correct as those from the gravimetric method, but on account of the ease of manipulation and speed of working it is used when high accuracy is not needed.

Gases are always analysed volumetrically, except in a few cases.

Another useful division of analytical chemistry is into inorganic and organic. The above principles and methods, which are essentially an inorganic development, may frequently be applied, but in general results are not so readily obtained. The identity of a compound is more often to be established only by its complete breaking up into substances of simple composition. This is the more readily possible, as most organic substances are decomposed by heat, and under established conditions the proportions of the component atoms can be ascertained. Such physical properties as melting and boiling points are of great importance in recognising a substance, and a much more frequent employment of them is usually necessary in organic analysis than in inorganic.

Recently these various general methods have been adopted, by a specially devised technique, for the examination of very small quantities of substances, and have collectively become known as *micro-analysis*. The advantage of such work is found when the material is available in only very small quantities or is of a dangerous nature; much time may also be saved.

For qualitative work a suitably equipped microscope is essential, with such specialised apparatus as has been devised, and for quantitative determinations a micro-balance is equally necessary. The whole of this remarkable development of analytical procedure has led to the possibility of accurate results of analysis and also of the determination of molecular weights by physical methods, whilst employing quantities of materials of one-tenth to one-hundredth and even less the usual amounts.

GOVERNMENT CHEMICAL ORGANISATIONS.

An account of a police-court prosecution or the summary of a departmental annual report in the Press is all the public usually hears of the great organisation that the Government maintains for safeguarding the health of the country and the safety of the Empire. The following short account gives a view of what is being done.

The *Government laboratory* is of most immediate interest, as it possesses the ultimate control of the nature and quality of the foodstuffs and drugs available to the public, and of the fertilisers and feeding stuffs of all kinds available to the farmer. Thus it is the unobtrusive but powerful protector of our lives from moment to moment.

It originally started for the examination of tobacco for adulteration; then it spread to cover other excisable commodities, and finally to deal with the much wider sphere of chemical activities that it covers to-day.

This now includes advisory and investigatory work for the various ministries, offices, and departments, and a great variety of problems from other official sources. No work is accepted from private individuals except in accordance with specified regulations.

The *Ministry of Health* is the body that makes the detailed arrangements for public protection under the Sale of Foods and Drugs Act. It requires local authorities of all counties and boroughs to appoint officials to take samples of those materials that are offered for public consumption, and the public analysts to analyse them. Under analogous Acts, water, drainage, sewage, and rivers are all watched, by means of chemical and bacterial examination, by highly qualified men also appointed by local authorities. The health and lives of workpeople are safeguarded by the factory inspectors, as well as the country and inhabitants surrounding chemical factories.

The *Ministry of Agriculture and Fisheries* acts in a manner comparable to the Ministry of Health and its connection with foods and drugs, by requiring a similar type of service to sample and examine the nature and quality of fertilisers and agricultural foodstuffs.

The *Gas Examiners* are appointed by the local authorities to carry out the analysis of the gas produced by all gasworks of the country, according to the prescription of the Gas Referees, who are appointed by the Board of Trade. In this way the public is protected as regards the heating power and freedom from deleterious constituents of the gas that is supplied to it.

In less direct contact with the man in the street or on the land are the great organisations and laboratories dealing with broader national and imperial matters.

There is the Scientific and Technical Department of the *Imperial Institute* of the United Kingdom, the Colonies, and India, that carries out investigations of the composition and utilisation of raw materials, and gives advice as to their growth and development.

Very important work is carried out by the *National Physical Laboratory* at Teddington. This started as a testing and standardising institution, but it gradually expanded until at present it is in a position to carry out research work, both in physics and chemistry, of the highest quality. It limits its work to matters of national importance for which little or no provision or opportunity is otherwise available.

Of the highest importance to our scientific national life is the *Department of Scientific and Industrial Research.* This is an organisation which institutes research on matters of wide importance, aids research laboratories that are established by various industries, and coordinates and distributes information to a specified extent. Its activities, which have recently been extended to Australia, are expanding in so many directions, including very highly important medical matters, that chemistry constitutes only a part of its great work. The National Physical Laboratory and the chemical laboratory of the *British Museum* are also under its direction.

In addition to these, passing mention only can be made to the research and analytical establishments of the *Admiralty, War Office, Air Ministry, India Office, London County Council,* and the *Royal Mint,* which are maintained only for their own specific purposes.

The perusal of this chapter must lead to the recognition that chemistry is one of the most important factors for the welfare of the Empire, and should occupy a high and honoured place in the national esteem.

CHAPTER VI

THE MODERN TREND OF CHEMISTRY

THE latest and most striking advances of modern chemistry, whether in pure or applied science, are in those regions that border upon the other sciences.

The importance and the startling nature of such work, which will be shortly considered, must not obscure our recognition and appreciation of the advances in chemistry that are proceeding along more orthodox and less sensational lines.

In INORGANIC and ORGANIC CHEMISTRY, pure and applied, only a very few examples can be examined here.

It is difficult to give a true expression of the value of research in pure chemistry, because there are no values that can be used as a basis that are currently and ordinarily recognised. The steady increase in the number of synthetic chemical substances produced and studied in the laboratory does not *seem* to have much value.

The statement that researches on the *sugars* are of importance to humanity may well court disbelief from the majority, because the fact is not clear that the work was of great value in the elucidation of their structure and that of cellulose and starch.

Synthesis of the *terpenes* has a slightly more obvious value, as these substances form the basis of the essential oils and of rubber. Still closer to the fringe of usefulness —apparently—and, therefore, to the approval of the "man in the street" is the work done on the *alkaloids*, the *fats* and *oils*, and the *proteins*—the substance of the living cell. Still stronger approval may be accorded the study of the *fermentation industries*.

It cannot, however, be too strongly emphasised that research in pure science is of high value in enriching the world's knowledge (so long as the subject taken for study is not fantastic), for its own sake, for its reflection on other sciences, and, perhaps at any moment, for its unexpected practical application to man's immediate needs. Increasing and ever-increasing stability of underlying theory is, ultimately and indirectly, of far better money value—particularly as the price paid for it is so low—than any return obtained immediately on a successful commercial process. The scientific world realises this; a few big industrial firms do so also; but, as a rule, results immediately convertible into money profit are all that are asked for and encouraged.

In the industrial world the following are the matters of outstanding interest that are being developed:

The most active among them is, probably, the *dye* industry, where competition for the world's favour is most acute. More and more of these wonderful substances are being made of increasing complexity of structure, and of increasing beauty of colour; and a special stimulus has been given by the particular problems attending the dyeing of artificial silk.

Important researches on *glass* are establishing and widening our scientific outlook and technical knowledge. It was the lack of this that left us all but helpless at the beginning of the war, owing to our dependence on foreign products. It was only the brilliant high-pressure work of the chemist that saved the country in this direction, as in many others.

A great deal of quiet investigation has been proceeding for a long time on the *cracking of oil*. When petroleum is distilled in order to separate it into its useful constituent parts, petrol is more valuable than some of the heavy oils. If these are strongly heated, they are broken down, partly into light oils that can be added to the true natural petrol and be used in it. In this way a large increase is made in the supply of petrol for the world's use, but work is continuously being carried on as the process is not technically perfect.

More has been heard by the public of *low temperature carbonisation of coal.* As a rule coal is carbonised at a high temperature, and there result the well-known products of gas, tar, and coke. But if the operation is carried out at a lower temperature there are obtained a gas of a richer nature, tar of a peculiar quality which may be applied, as such or after refining, for power purposes, and a solid fuel suitable for the domestic hearth, which, at the same time, does not give rise to smoke. A large amount of work has been done on the problem—which is largely also an economic one—and it is still going on.

In Physical Chemistry there are three very important groups of researches that are characteristic of modern progress—atomic structure, colloidal chemistry, and catalysis.

The examination of *atomic structure* has already been referred to in connection with the development of the atomic theory, and is being more fully described in another volume. One fundamental application that is being made of these researches is the attempt to apply this knowledge directly to the explanation of the phenomena of chemical activity, of which the mainspring has long eluded discovery. One hypothesis, that is likely to be found to contain much truth, suggests that chemical valency and chemical combination result from a tendency to unite of atoms containing unequal numbers of electrons, the sharing together of which constitutes chemical combination and usually results in an increased degree of stability of the whole reacting system.

Colloidal Chemistry has been somewhat vaguely recognised as a section of its own ever since Graham, in 1861, differentiated the crystalline from the jelly and gum-like substances. He recognised that in many important properties these two types of substances were wholly different, but on account of the very great difficulties of investigation and the queer results that were obtained for some time, this branch of chemistry has only made real progress during recent years.

Research has shown that the difference between crystalloids and colloids is primarily one of subdivision. A crystal is a relatively big thing which has formed in an orderly fashion; a colloid substance is a congeries of extremely minute particles. Crystalline substances, including metals, have been obtained in colloidal form; colloids have been persuaded to crystallise. Both, therefore, are conditions of state which depends on the method by which the substance has been produced.

The particles of a colloid body, whether solid or liquid, begin to show their characteristic properties when about one-thousandth millimetre in diameter, and they have been traced by optical means till they are so small that each particle consisted of only a few molecules each. The interrelation of the dimensions of a sphere is that mass is proportional to the cube of the diameter, and surface is proportional to the square of the diameter; so when a particle becomes smaller and smaller the surface area diminishes at a less rate than does the mass until at last the surface is so much greater in proportion to the mass that surface activities—surface tension, surface attractions—have a greater effect on the particle than does gravity. One immediate result of this is that the particles will not sink in a liquid—gravity has not sufficient pull to overcome the local influences—and yet the particles are not so small as to consist of free molecules. Thus a kind of solution has been formed; not a true one, but a "colloidal solution."

Such a liquid, known as a "suspension" in the case of solids and an "emulsion" in the case of liquids, may be rendered more stable by the presence of other colloids which "protect" the primary one and keep it in its original state. Thus "colloid chemistry" has come to mean "the chemistry of minute particles," whether they consist of solids, liquids, or gases, "dispersed" amongst one or other of the states of matter in "continuous phase."

To the colloidal condition is due the many extraordinary conditions, activities, and effects of high scientific and industrial value.

The more obvious and, therefore, striking examples taken from everyday life are: the curious behaviour of gelatine and its swelling; egg albumen and its solidification through heat or salt; the peculiarities of soap solutions; the gorgeous red colour given by gold to glass; the natures of mist and fog and foam; the strength of the cobweb and of silk; and, as all living things are almost wholly colloidal, perhaps the possibility of life itself.

A glimpse will have been obtained of the vista opened up by the study of these substances, and a consideration of two of them only will be given as examples of substances that are of great importance at the present time. Man might get on without his crystals, but not without his colloids.

Cellulose is a protean substance, as it appears in the form of cotton, paper, artificial silk, and aeroplane dope, photographic films, explosives, and celluloid.

From the cotton plant is obtained the purest natural cellulose, which, after treatment, is converted into guncotton by the action of, primarily, nitric acid. Less far-reaching action of the acid gives a substance used for the preparation of photographic films, and a still less energetic nitration gives a product suitable for mixing with alcohol and camphor for the production of celluloid.

Paper used to be made exclusively from cotton or linen, but nowadays a large proportion, especially that used for newspapers, is prepared from wood pulp; that is to say, from the purified cellulose of trees.

The most sensational development of the use of cellulose has been in the production of artificial silk—the formation of cellulose fibre in imitation of the gum fibre that is natural silk. The principle depends on obtaining a solution of cellulose, squirting it into a fine thread, and regenerating the cellulose (or a compound) in an insoluble form. There are no less than four ways of doing this—through a soluble nitrate of cellulose, by solution in a solution of copper sulphate and ammonia, as an alkaline sulphur compound, as an acetate. The last but one is of interest, as it appears to be slowly ousting the others, and the last because it is also used as a non-inflammable cinematograph film and "dope" for the tightening and protection of aeroplane fabric.

Innumerable problems of manufacture had to be solved before the product could be made sufficiently acceptable to the public, including the effect of water, and the dependence of regularity of dyeing on the type of artificial silk used, on slight variations in its manufacture, and on the nature of the dye employed.

The other colloidal substance of great importance is *rubber*, which is continually increasing the number of its uses. It is obtained from several trees and plants in the form of a watery emulsion known as "latex." This contains also resin, nitrogen-containing bodies, and sugars, wherein is mixed the rubber in the form of globules that may have a diameter of 0·5-3 thousandths of a millimetre. These are brought together and made sufficiently solid by causing coagulation to take place, a characteristic colloid phenomenon. After separation it is redissolved for use, and its slow swelling and final change into a viscous liquid is typically colloidal behaviour.

The natural inferior elasticity of rubber is raised to a technical value by "vulcanisation"—heating with sulphur and usually with "accelerators" at the same time. With a higher proportion of sulphur, ebonite is produced. For long the nature of this change has been sought by chemical means, and no satisfactory end has been reached. Purely physical chemical methods have also been only partially successful; perhaps a consideration of the possibility of both types of activity occurring together will lead to firm knowledge.

Inquisitiveness and foresight have led to attempts to synthesise rubber, from the days of Faraday (1826) onwards. It has finally been found that no substance can be made to give an exact reproduction of natural rubber, but several can yield a material sufficiently like rubber to be technically valuable—at a price.

Isoprene (C_5H_8), obtained from turpentine, from the amyl alcohols, from the pentanes in petroleum, from para-cresol in coal tar, and from other substances, can be coagulated to a rubber-like substance of the same formula as true rubber ($C_{30}H_{48}$), the suggestion for the use of this substance coming from its presence in the products of distillation of rubber itself.

Butadiene (C_4H_6), a substance of slightly simpler composition than isoprene, is also used and may be obtained from butylene (in petroleum) and its derivatives, and from more complex compounds altogether.

Coagulation can be brought about by most varied means—heat, light, and chemical substances—and the properties, both physical and chemical, of the product depend to a great extent on the method employed.

It seems, therefore, that the problem is so near solution that it only wants economic pressure to give the final impetus towards production on the large scale of a material which, if not as good as natural rubber, will at any rate be a technically useful product.

Catalysis is a physico-chemical activity by means of which chemical reaction between substances is assisted by another substance whose presence is essential, but which remains unchanged in quantity at the end of the reaction. The words "in quantity" are important, because there may be an alteration in the state of the catalyst. A crystalline material is found to be changed to a powder; a smooth metal surface becomes pitted and ragged.

Examples of this have long been known, and from among others the following may be quoted: in the manufacture of sulphuric acid the essential change is the combination of sulphur dioxide with oxygen to form sulphur trioxide. Simple mixture of the two gases is of no use, but in the presence of certain oxides of nitrogen or of platinum the change goes on indefinitely with no loss of the catalysing agent.

In recent years, however, the use of catalysing agents has increased enormously, with an accompanying profound change in the nature and scope of some sections of chemical industry.

The preparation of oxides of nitrogen, whether for use in the above-mentioned manufacture of sulphuric acid or for the production of nitrates as fertilisers, and also the production of ammonia for the latter purpose, are good examples of the employment of catalysts.

In one type of process, nitrogen and hydrogen are made to combine under high pressures and rather high temperatures in the presence of iron as a catalyst with another substance acting as a " promoter." That means that the catalyst stimulates the reaction, and the promoter stimulates the catalyst. The hydrogen for the process is made in several ways, one of which is by passing " water gas " (consisting mainly of carbon monoxide) and steam over a catalyst, which causes the production of carbon dioxide and hydrogen from the mixture, according to the equation—

$$\begin{array}{ccccccc} CO & + & H_2O & = & CO_2 & + & H_2 \\ \text{(Carbon monoxide)} & & \text{(Steam)} & & \text{(Carbon dioxide)} & & \text{(Hydrogen)} \end{array}$$

The carbon dioxide is removed and the purified hydrogen is employed for the reaction.

The ammonia, formed as described (or obtained from other sources), may be passed, mixed with oxygen over a catalyst—in this case heated platinum gauze—when reaction takes place whereby oxides of nitrogen are formed, which, on absorption in water, are converted into nitric acid, and this, in turn, is used to form nitrate.

A very important technical application of a catalyst is in the oil industry, where a liquid oil is converted into a solid fat by the addition to the oil molecule of hydrogen. In this way materials of varying degrees of hardness can be prepared according to industrial requirements. The essence of the process consists in passing hydrogen through the chosen oil—earth nut oil, cotton seed, whale, or others—in the presence of finely divided nickel, which acts as the catalyst. A large and valuable industry has been established on the basis of this queer phenomenon.

A very remarkable process has been developed at the works at Shawinigan Falls in Canada. Here the electric furnaces produce calcium carbide which, on contact with water, generates the gas acetylene. This gas, when passed through water containing a mercury compound as catalyst, becomes converted into acetaldehyde. This can be easily oxidised to acetic acid, which is a valuable substance, and which can be further changed into acetone, a useful general solvent and an essential one in the manufacture of cordite. Or the acetylene may be passed through a solution, for instance, of hydrogen peroxide (H_2O_2; compare water, H_2O) in presence of a mercury catalyst, when acetic acid is formed directly.

An entirely different type of catalyst is the enzymes, organic substances that are found in living animal and vegetable organisms. They assist in the decomposition of complex bodies, as in digestion, and in other vital processes.

A further example of catalytic action is in the trace of water vapour that must be present in many chemical actions—so many that it is thought to be essentially necessary for the possibility of chemical change. To mention only one well-known example: perfectly dry chlorine gas can be left in contact with aluminium foil indefinitely, but if a trace of water be introduced, chemical reaction takes place instantly and aluminium chloride is formed.

It has been found, too, that some of the properties of substances that have been intensively dried for years have undergone considerable modification. All of this indicates the extraordinary influence of minute traces of water.

It will have been realised by now what a remarkable phenomenon catalysis is, and with what almost magical powers the chemist has endowed himself by patient and minutely careful work.

The understanding of the underlying cause of this effect is incomplete but increasing. It was soon realised to be a surface phenomenon that the chemical changes took place by the assistance of the surface molecules of the catalyst, and it has recently been found that the activity at various parts of such a surface varies with its texture and physical nature. This is a rather special case of the wider phenomenon of " adsorption "—a kind of temporary condensation of one substance on to the surface of the catalyst in a state of extreme division; or of molecular posture on the catalyst's surface, like corn in the cornfield, that enables the free ends to react the more easily with the other substance. There can be little doubt that there is temporary combination with, and subsequent detachment from, the surface of the catalyst, but the forces directing and the conditions permitting these changes are still obscure.

The intimate connection between colloid chemistry and catalytic activities will have become obvious through their both depending on surface for the production of their phenomena.

The art of *photography* grew up, to a great extent, as a result of empirical work having little scientific basis; the science of photography is of recent growth.

Its development in competition for popular favour on the one hand, and on the other its ever-growing value as a weapon of research in many types of work, and a means of record of very wide application, has given rise to a long series of valuable researches that are still proceeding.

Such researches obviously must cover the minute examination of all the properties of the materials used; of the fineness of grain of the silver compounds in the film; of the changes due to development, fixing, sensitising, and the rest; of the action of light and the speed at which its results are produced; and a host of others that are too technical to mention.

There always remained one crucial mystery: What caused the changes in the grains of the silver compound as a result of the impact of light? Only as late as 1923 was this solved, when it was found that in certain gelatines there occurred very small traces of sulphur-nitrogen compounds, and of these the thiocarbamides interact with the silver compounds and produce nuclei of silver sulphide which are the " sensitivity centres " of the photographic film; a brilliant piece of research.

The scientific side of photography is extremely complex and demands the highest scientific abilities for the elucidation of its problems. The amateur who presses a button and sends his films to be developed and printed has no conception of the high level of the work that has been done for his satisfaction.

It is unfortunate that it is impossible in a small volume to give more than one or two glimpses of the remarkable work that is being done in *biochemistry*.

Amongst other lines of research, very minute attention has been given to vitamins, hormones, changes in the constituents of the blood in health and disease, specific chemical attack on invading micro-organisms, the position taken by compounds of phosphorus, sulphur, calcium, iodine, and others in the fundamental well-being of the body, the highly complex changes going on during digestion, and the reconstruction of the broken-down simpler molecules into the complex constituents of living things. Even when the pure chemistry is understood—and complete understanding is not frequent—the problems are greatly complicated by the still imperfectly elucidated colloidal phenomena.

Most has, perhaps, been heard about *vitamins*, substances of unknown chemical composition that exist in minute quantities in certain foodstuffs. They are essential to general health, and recent experiments tend to show that they control fecundity in animals and might even be found to control the sex of a next generation.

The most famous of these vitamins is vitamin D, deficiency in which is the cause of rickets. This disease may be combated by feeding with food materials containing the vitamin. Also, most remarkably, the deficiency may be made up by treatment with sunlight, which causes the individual to make his own supply of vitamin. Still more remarkable was the discovery that good results could be obtained by the act of light rays, not on the patient, but on the different foods he ate. One wonders whether the instinctive satisfaction of eating fruit " straight off the tree " is not due to the beneficial consumption of freshly irradiated food.

Immunity from many diseases can be obtained, as is well known, by the injection of a prepared serum, consisting of dead bacteria or of the poison they produce. (Only in vaccination against smallpox are the live micro-organisms injected.) The effect of such injection is to produce in the blood a capacity to resist the attack of the actual disease germs. It is remarkable that such immunity has been rendered specific only against the particular disease organism in question. It would seem not only that the matter is mainly a chemical one, but that, in some cases, at any rate, the substances involved are peculiar carbohydrates, the same wide class of substances that include sugars, starch, cellulose, and dextrin.

The type of reaction that occurs in this branch of chemistry is unusual and has required a specialised technique of its own. Being essentially a chemistry of the blood, other valuable information has been obtained from its study.

For instance, it is well known that, among human beings, there are several types of blood, a fact of vital importance when transfusions of blood are being given.

If the wrong type of blood is transfused the patient dies in convulsions. Blood is tested by the application of the "precipitin" test, and an application of this has been made for the degree of relationship of human beings with various types of primates. The results are so remarkable as to deserve space here.

Blood Tested.	*Precipitate.* Per Cent.
34 specimens of humans	100
8 specimens of anthropoids	100
36 specimens of common monkeys	92
13 specimens of capuchins and spider monkeys	78
4 specimens of marmosets	58
2 specimens of lemurs	0

(After Wells, by the courtesy of the Publishers; see Bibliography.)

Chemotherapy is, to some extent, a more definite chemical attack on disease. It includes substances employed for external antisepsis and for internal use for killing or immobilising the invading unicellular micro-organism by direct chemical means; and the margin of safety in doing this without damage to the patient, who also consists of cells, is narrow.

The first attempt was the now long-established treatment of malaria with quinine. Then later came the idea, which was subsequently found to be only partially true as regards its theory, of killing the disease germs by dyeing them—by combining with them certain substances having a specific and selective attack on wall tissue or internal protoplasm, in the same way that dyes act on fibres and stains on microscopical specimens. Later still came the injection of complex organic compounds, sometimes containing in the molecule mercury, arsenic, antimony, and other such elements, which have, as research continues, greater and greater advantages in curative power and fewer disadvantages in their effect on the injected human body. The work is proceeding with great energy, but is retarded by the delay in the full development of the underlying theory.

CHAPTER VII

THE FUTURE DIRECTION OF CHEMICAL PROGRESS

Prophecy, as commonly understood, is miraculous and therefore repugnant to the scientific mind, but "intelligent anticipation" that is really intelligent is often possible and frequently desirable, and is the more trustworthy the smaller the distance in time that the mind is thrown forward.

In the case of chemistry, the youthful but definite development of many of the directions of recent research leaves little doubt as to the immediate future.

Catalysis, with or without high-pressure reactions—and high-pressure reactions, with or without catalysis—will be developed to such a degree as to transform the outward appearance of chemical industry.

Already a remarkable development in the use of coal is emerging from the condition of laboratory experiment to the larger scale of industrial examination. It has been found that when coal at a raised temperature is treated with hydrogen at a high pressure in the presence of a catalyst, a considerable proportion of the coal is transformed into oil. It is a matter of further research to increase that percentage; but there is no doubt as to a greatly increased consumption of coal for the production of liquid fuel. This protection of coal against the onslaught and invasion of oil and water power will be an interesting parallel to the saving of gas for lighting purposes, in face of the attack by electricity, by the invention of the incandescent mantle; and when the incandescent mantle threatened to outdo electricity with its carbon filament lamp, metal filament lamps came to its aid and re-established the closeness of the race for public favour.

There will be a large increase in the practical application of chemical synthesis for the purposes of imitating and replacing the products of Nature.

The synthetic production of silk has already been touched on, and perhaps the demand for rubber for rubber roads—which, I think, is an inevitable development—may encourage the production of the synthetic product.

The imitation of ornamental and semi-ornamental stones from waste milk products has been going on for some time, and the imitation or replacement of natural resins, together with the production of a greatly extended range of properties, has been developed with very valuable industrial results, even to the possible provision of a supplemental material for lenses of peculiar properties.

The production of fatty acids—usually obtained from fats and oils—has been achieved from paraffin wax, and certain coal tar products have been modified so as to be able to compete with turpentine for use in paints.

The synthetic production of indigo and alizarin has long been established as a great industry, and synthetic camphor is becoming more and more a well-known and valued material.

The remarkable, almost magical, effects on the health and development of the individual that are effected by the hormones—the minute quantities of secretion of the ductless glands that find their way into the blood stream—have been studied only a relatively short time, and yet already the active principle of one of them (suprarenine) is a commercial product of the synthetic laboratory. More and more of the natural drugs are being studied and elaborated; doubtless these and entirely new ones will be synthesised in the future.

There remains for mention a remarkable series of synthesis, the more remarkable as it is being carried out in a manner very close to Nature's own. The production of sugars and something very like alkaloids has been carried out in the laboratory by the action of filtered ultra-violet rays on a mixture of carbon dioxide and water vapour for the production of sugars, together with simple nitrogen compounds for the production of alkaloid-like substances. Not only is this a wonderful chemical achievement, but it is the more interesting as being one of the very few examples of an imitation of the gentler natural way of achieving results as compared with the more usual violent laboratory methods. For the time being there seems to be little likelihood of commercial application of this discovery, but undoubtedly this type of synthesis will be employed with an increasingly widening sphere of application.

Looking at the subject from a broader aspect, the mode of insuring continuous advances in theoretical and industrial chemistry will be in still further elaboration of the existing machinery of endowment and for teamwork in research. Not only must the schemes of research scholarships and endowment funds inevitably be extended, but more and more will teamwork between individuals, organisations, and sciences be developed. The increasing complication of the individual sections of science and the increasing complexity of the problems to be solved will compel collaboration to an ever-increasing degree, until a point will be reached when, in my personal opinion, the one stupendous problem of the universe will be approached and solved in the following manner:

In no very great distance in time a far more profound view of atomic structure than at present obtains will be achieved, when the arrangements of all the electrons around the proton will have been ascertained for all the elements, as well as the significance of these arrangements as controlling the associated properties of the elements, and of the cause and mode of chemical reactions and degrees of chemical stability.

Colloidal chemistry will soon be out of its swaddling clothes, and will then quickly set out on its way to a vigorous maturity.

As soon as biochemistry has, by its own researches and with the help of the two other branches just mentioned, solved the problems of the composition and behaviour of protoplasm, and its synthesis from simpler substances, the way will be prepared for the most wonderful research of all. The knowledge of the fundamental composition of matter, together with that of the inter-relationship between matter and energy, the understanding of the behaviour of colloidal substances, and the comprehension of biological chemical activities, will all co-operate in the elucidation of the very nature of life itself. The stage will be set and the actors ready for this most enthralling drama; and when finally the call of " Author!" is made, Human Intelligence—whatever may be behind it—will take the curtain.

BIBLIOGRAPHY

CHAPTER III

I. Masson: *Three Centuries of Chemistry.* Ernest Benn, Ltd. 1925.

H. Stanley Redgrove: *Alchemy, Ancient and Modern.* W. Rider and Son, Ltd. 1911.

J. M. Stillman: *The Story of Early Chemistry.* D. Appleton and Co. 1924.

CHAPTER IV

Ida Freund: *The Study of Chemical Composition.* Cambridge University Press. 1904.

J. W. Mellor: *Modern Inorganic Chemistry.* Longmans Green and Co. 1925.

I. Remsen and W. R. Orndorff: *Organic Chemistry.* Macmillan and Co., Ltd.

Percy E. Spielmann: *The Genesis of Petroleum.* Ernest Benn, Ltd. 1923.

CHAPTER V

R. B. Pilcher: *The Profession of Chemistry.* Constable and Co. 1919.

Institute of Chemistry of Great Britain and Ireland: *Official Chemical Appointments.* 1924.

CHAPTER VI

Edited by E. F. Armstrong: *Chemistry in the Twentieth Century.* Ernest Benn, Ltd. 1924.

A. W. Stewart: *Recent Advances in Physical and Inorganic Chemistry*. Longmans Green and Co., Ltd. 1926.

S. T. Levy: *An Introduction to Industrial Chemistry*. G. Bell and Sons, Ltd. 1926.

R. B. Pilcher and F. Butler Jones: *What Industry owes to Chemical Science*. Constable and Co., Ltd. 1918.

C. H. Lander and R. F. McKay: *Low Temperature Carbonisation*. Ernest Benn, Ltd. 1924.

H. Freundich: *Elements of Colloid Chemistry*. Methuen and Co., Ltd. 1925.

B. D. W. Luff: *Chemistry of Rubber*. Ernest Benn, Ltd. 1923.

S. P. Schotz: *Synthetic Rubber*. Ernest Benn, Ltd. 1926.

E. K. Rideal and H. S. Taylor: *Catalysis in Theory and Practice*. Macmillan and Co., Ltd. 1919.

E. K. Rideal: *Surface Chemistry*. Cambridge University Press. 1926.

G. R. Partington and L. Parker: *The Nitrogen Industry*. Constable and Co., Ltd. 1922.

Photography as a Scientific Implement. A collective work. Blackie and Son, Ltd. 1923.

Physical Chemistry of the Photographic Process. A general discussion. The Faraday Society. 1923.

Monographs, 1921 onwards, and Abridged Scientific Publications from the research laboratories of the Eastman Kodak Company. Highly scientific. 1913 onwards.

J. Pryde: *Recent Advances in Biochemistry*. J. and A. Churchill. 1926.

H. Gideon Wells: *The Chemical Aspects of Immunity*. The Chemical Catalogue Co. Inc. 1925.

THE ORIGINS OF AGRICULTURE

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THE ORIGINS OF AGRICULTURE

By HAROLD PEAKE, M.A., F.S.A.

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PREFACE

The practice of agriculture has produced such a marked change in the life of mankind that its origin cannot be a matter of indifference to those interested in the evolution of civilization. In spite of the many discoveries made during the last few years, we have not yet succeeded in tracing the history of the Near East back to the days when corn growing was in its infancy. Still, though these beginnings are not yet in sight, we may feel confident that they did not long precede those times, remains from which are now being laid bare in Mesopotamia. The actual origin of agriculture, therefore, still remains a matter of inference, and for that reason I have felt it necessary to emphasize, at the risk of becoming tedious, the distinction between possibilities, probabilities, and well-ascertained facts. Readers who are desirous of carrying their investigations into this question back to original sources will find full references to most of the facts relating to early agriculture cited in this volume in my Presidential Address, entitled, "The Beginnings of Civilization," published in the *Journal of the Royal Anthropological Institute*, LVII., 19-38.

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THE ORIGINS OF AGRICULTURE

CHAPTER I

THE PROBLEM

Few people realize that their daily bread, accepted as a matter of course, is the result of a most important discovery. Yet this discovery, that the seed of certain grasses, cast on the upturned ground, would bring forth a hundredfold, and that such seeds were an almost perfect food for humanity, changed the whole outlook of mankind. Till then man had been a savage, preying on such large beasts as he was able to slay, or collecting smaller game, shell-fish and even insects. The discovery that grain crops could be raised at will placed his feet upon the first rung of the ladder of civilization. This momentous discovery once made, men lived in villages instead of wandering after their prey, the villages became towns, one discovery followed another until in a surprisingly short time true civilization was achieved.

There are people still living, such as the Bushmen in the deserts of South Africa, and the Black Fellows of Australia, who have not yet made this first step on the road of progress, and from their methods of living we can learn something of the life of our ancestors and predecessors in pre-agricultural times. The life of these people, especially that of the Bushmen, is one long and hungry chase, often fruitless for days at a time; then, when success has at length rewarded their efforts, they sit down and gorge, then rest awhile to recover from this state of repletion. Others, like the dwellers in Tierra del Fuego, live largely on fish and molluscs, a most unsustaining diet, and, though such food can be obtained with greater regularity, most of the day must be spent in collecting supplies, and there is little if any time over in which to make advances towards civilization.

Those who have studied the far past history of the human race, and have pieced together with laborious care the evidence obtained from stone implements and the refuse left around the camp fires of the folk that made them, tell the same tale of the early peoples of Europe and elsewhere. Throughout the Old Stone Age, which lasted, it is believed, for hundreds of thousands of years, man lived entirely on the products of the chase. He was a hunter and a savage. He produced no food, but exploited the wild resources of Nature.

It has often been stated that man has passed through three successive stages of civilization. These are known as the Hunting, Pastoral, and Agricultural stages. It is now known that this statement is not strictly accurate in all cases; nevertheless, it is useful to think of them as three important rungs in the ladder, for no advanced civilization has been achieved until the agricultural stage has been reached.

Of the Hunting stage, something has already been said, but it may not be amiss to describe it in greater detail. It is generally believed that the first truly human beings hunted in packs the wild animals of the grasslands, and that it was this combined action, and the fact that they found it better to travel on two legs than on four, that caused the first men to become different from their ape-like ancestors, or perhaps it was because they thus differed from the forest-dwelling apes that they took to hunting on two legs in the open grasslands.

In the earliest days, it is believed, the women hunted with the men and shared equally with the other sex the products of the chase. Sometimes, however, the cares of maternity caused them to drop out of the band for a time, though, after a very short interval, they resumed their places in the group, carrying their new-born infants, if these had survived. By degrees these intervals grew longer as the women paid more attention to the rearing of their young. This caused the women to stay longer away from the men and to form temporary or sometimes permanent homes, to which the hunting pack returned at intervals with part of its spoils. Thus the hunting areas became more and more restricted, and a home for the pack grew up, or perhaps several homes suitable for different seasons of the year. So long as the game was plentiful and the population not too great, this limitation of the hunting lands made little difference, but, when the population increased, as it did when the young were better cared for, and when the men became more expert hunters and killed more frequently, the game became scarcer and the food supply diminished. This scarcity, inevitable in time in most parts of the world, caused various changes to take place in the habits of the tribe.

The increased attachment of the women to their homes, necessitated by the prolonged attention given to their children, caused them to be absent for longer periods from the hunting pack, until at last hunting came to be looked upon as the occupation of men, while woman's sphere was restricted to the home. There were times of leisure for these women, and there were times when the food supplies, brought at intervals by their men-folk, ran out; it became customary, therefore, for these women to supplement their diet with nuts and berries collected at no great distance from their homes. Thus, as game became scarcer, the meat became more and more the perquisite of the men, while the women took more and more to a vegetarian diet.

It sometimes happened that the supply of game became quite exhausted. This was more commonly the case when, owing to changes in the climate, forests sprang up where there had formerly been open grasslands. Then the more active men moved off to the drier lands, where open conditions still continued, while the less enterprising had to abandon the chase and to settle down by the seashore, or by the banks of lakes and rivers, where they searched for other food. Small animals were still to be found, though with difficulty, these were more often trapped than hunted. Fish could be caught, and by the sea many articles, suitable for food, were cast up by the waves after a storm. The main diet of these men consisted, however, of molluscs, and large heaps of the shells of limpets and other molluscs, found still by the seashore in Denmark, Scotland, Japan, and British Columbia, and in many other parts of the world, show us to what an extent such people lived upon a diet of shellfish. Molluscs, however, are not a very sustaining food, and vast quantities had to be collected to keep body and soul together. It seems likely that these men, thus reduced to the collecting stage, had to abandon their prejudices, and to share the supplies of nuts and berries collected by their women, and perhaps to supplement this vegetable diet by digging up some edible roots.

We must now follow the fortunes of those more active hunters, who dwelt on the open grasslands. These followed herds of various hoofed animals, antelopes, bison, or wild cattle, and by an organized system of chase kept themselves well supplied with meat. How this was done we have learned from the customs followed not so long ago by the natives of the American prairies. These American Indians were wont to hunt the large herds of bison that roamed the great grasslands of North America. Bands of men followed these herds of bison on foot all day long, keeping them constantly on the move, while the women and children followed them at a slower pace. Though the hunters rarely caught up the herd, they were enabled to keep the bison moving at such a pace that the weakly animals fell behind, and became a ready prey to their pursuers. In this way a constant supply of fresh meat was obtained, and after a beast had been killed a halt was called for a few days to enable the women and children to come up.

It seems probable that other hunters chased wild cattle on the grasslands of South Russia and Turkestan, using methods not unlike those known to have been employed by the Indians of the American prairies. Wild oxen are accustomed to spend the winter in scrub country on the edge of forests, and here their calves are born. There were extensive parklands, consisting of groves and thickets scattered through the grassland, just north of the open steppelands of South Russia. Here the cattle must have congregated when the snow lay deep in midwinter, and here the calves must have been born in the early spring. When, however, the fresh green grass sprang up on the steppes, the cattle with their young, now old enough to keep up with their parents, wandered over the rich grasslands that stretched from the foot of the Carpathian Mountains to the slopes of the Hindu Kush. Here, too, so we believe, they were followed in early days by bands of hunters, who may well have used tactics very similar to, if not identical with, those known to have been employed by the Redskins on the American prairies almost within our memory.

How cattle were first domesticated has given rise to much speculation, and there is considerable difference of opinion on this question. From the nature of the case, and the early date at which this advance in civilization was made, we can never be absolutely certain. It seems likely, however, that the men of South Russia and Turkestan followed herds of wild cattle on the steppes as the American Indians followed the bison on the prairies. By degrees, however, they succeeded in controlling the movements of the herds, keeping them stationary at night, perhaps by means of surrounding them with camp fires, until the herds grew more accustomed to their followers. Little by little this intimacy would increase until the cattle became relatively tame, and in due course the women had persuaded some of the cows to share their supply of milk between the calves and the babies. Be this as it may, we have much evidence pointing to South Russia and Turkestan as being one of the earliest, perhaps the very earliest, region in which cattle were tamed. Sheep, which inhabit more elevated regions, seem to have been domesticated in a somewhat similar fashion in the higher areas of Turkestan, while the goat was tamed in a mountain district, probably further to the south. It is not, however, possible at the present moment to speak of any of these matters with certainty.

Pastoral peoples, following their herds of domesticated animals, have an assured food supply, for they can take toll of their flocks, or herds at any time that the larder needs replenishing, besides which they have an abundant supply of milk and, as fresh discoveries are made, of butter and cheese. The herding and tending of such animals is a light occupation and one that can be handed over in a great measure to women and children. Thus pastoral men have considerable leisure in which to make advances in civilization. On the other hand, large herds of cattle soon eat the country bare and need constantly to be driven from one pasture to another. The pastoral tribe must, therefore, be ever on the move, so that it can carry little about with it, and its possessions other than live stock must be few and not too heavy or bulky. Thus pastoral peoples have made but small advances in material culture.

If, however, the material advance of pastoral peoples has been slight, their contributions to civilization have been by no means negligible. To drive large herds of cattle requires considerable organization, as, indeed, was to some extent necessary in the old hunting days. Thus pastoral society was well organized, usually on a patriarchal basis, the supreme command of the tribe being vested in an old man, theoretically the father of his people, while his power was to some extent limited by a council of elders, formed by his brothers or cousins. To keep the band together, strict discipline was necessary, and this became the more urgent when the tribe had to fight others to retain its customary pastures. Thus social organization, usually under a chief whose autocratic powers were to some extent limited by a council of elders, is well developed in most pastoral tribes, and is one of their great contributions to civilization.

The pastoral man has much leisure and time for contemplation, often in solitude. He has, therefore, speculated upon the origin of things and noted, and perhaps studied, various natural phenomena—the sun, moon, stars, wind, rain, storm, and the like. From these elements he has formed a philosophy of the universe and imagined supernatural powers, usually organized under one supreme head. Thus he has been the first to elaborate an organized religion, with deities to be worshipped rather than demons to be feared, and his organization under one supreme patriarch has led him to place his minor deities under one supreme god, who has ultimately supplanted the lesser powers. Thus most, if not all, of the great religions of the world, especially those with monotheistic tendencies, have arisen among pastoral peoples, though they have frequently degenerated into polytheism when the pastoral tribes have conquered a number of settled agricultural communities and adopted into their system, though usually into an inferior position, the gods of the conquered people. Social organization on a large scale and religion with monotheistic tendencies are the great contributions to civilization of pastoral man.

As has already been stated, it was formerly believed that all civilized people had passed successively through the hunting, pastoral, and agricultural stages. This we now know was not the case, at any rate in some instances. On the confines of Mesopotamia, though actually situated in Persia, lies the site of Susa, the Biblical Shushan, once the winter capital of the Persian kings. Here some years ago French explorers found the remains of several successive settlements, lying one above the other. The lowest of these settlements is one of the earliest yet discovered. Among the remains from this settlement were bones, pronounced by experts to be only those of wild animals, and this shows that the people inhabiting it possessed no domesticated animals, except, perhaps, the dog, which has been tamed by many hunting peoples. On the other hand, they made fine painted pottery, had copper axes, and seem to have practised agriculture. Here, then, we have a people, apparently growing grain, but possessing no domesticated animals and depending for meat upon the products of the chase. Other settlements in Mesopotamia, apparently of the same people, have been found on the site of the ancient city of Eridu, and, again, about four miles from the city of Ur of the Chaldees. These belonged, apparently, to the same people, for the pottery found there is almost identical with that discovered at Susa. These people were certainly growers of grain, for various agricultural implements have been found among their remains, but so far no bones of domesticated animals.

Near Anau, in Turkestan, Mr. Raphael Pumpelly excavated two sites nearly twenty years ago. In the bottom layer of the oldest settlement he found evidence of grain growing; in fact, he obtained impressions of wheat grains in some of the pottery, but, although there was ample evidence that these people practised agriculture, made painted pottery, and had a little copper, no traces of the bones of domesticated animals were found until the second layer. Thus we must believe that the cultivation of grain and the domestication of animals were two discoveries, made by two different groups of people, living in very different environments and with very different habits, though it was not long before the grain-growers became possessed of animals. On the other hand, the pastoral peoples took slowly to agriculture, partly owing to a disinclination to undertake steady manual work and partly to the unsuitability of their climate to grain cultivation. For one or both of these reasons, some of them, like the peoples of Mongolia, have remained purely pastoral to the present day.

Thus the hunters, constantly on the move after their game, which occupied the whole of their attention, could make no progress in civilization, while the pastoral folk, in spite of their leisure, lived a wandering life, and were unable to build permanent houses or to advance very far in material culture, though they made considerable progress in social organization and religion. The poor collectors lived a settled existence, it is true, but their whole time was taken up in gathering sufficient molluscs to keep body and soul together, and this type of food gave them so little sustenance that they had no energy for further experiments.

The growing of grain necessitated a fixed home, at any rate for the greater part of the year; it also provided such an ample supply of really sustaining food that it left the agricultural folk with some surplus energy with which to make experiments during the months of leisure between seed-time and harvest, and, again, between harvest and the succeeding seed-time. Having a fixed home, it was worth while to possess goods, and the potter's art soon came into existence. The discovery and use of certain metals, such as gold and copper, followed soon after, and not long after that the elements of writing. The knowledge of grain and the method of cultivating it having been achieved, all the main items of civilization were rapidly acquired.

The early grain-growers seem to have been peaceable folk, and doubtless suffered loss at times from the depredations of the hunters in the wastes around, or from the cattle of the pastoral folk in the adjoining grasslands. For this reason many of them joined forces and lived together in villages. In course of time many such villages became towns, trade arose, and civilization was well on its way.

From this brief sketch of what must have happened to hunters, collectors, pastoral and agricultural folk, it will be seen that it is the grain-growers only that made any real advance in material civilization. All our evidence goes to show that to them is due the potter's art and the knowledge of metals, the beginnings of writing, of architecture, and of trade. They were, in fact, responsible for almost all that we include under the name of civilization. It is, therefore, of no little interest to learn something of the beginnings of agriculture, which has worked such enormous changes in human life, and in the following pages an attempt will be made to solve the three questions: Where, when, and how did agriculture begin?

CHAPTER II

WHERE DID AGRICULTURE BEGIN?

MANY speculations have been made as to the region in which agriculture was first practised, and still more as to the places where civilization arose. As we have seen, the two centres must have been the same, for without the settled existence, impossible without an assured supply of adequately nourishing food, no advance in civilization was possible. It is quite obvious, when we think of it, that men must first have cultivated grain where grain-bearing plants grew wild, and so we may ignore all theories which suggest that civilization arose on the shores of the Baltic, or in any other region in which such plants do not grow wild, and in which, owing to climatic conditions, it is impossible that they should ever have done so.

All available evidence goes to show that men cultivated grain before they raised other vegetable crops, though there are some indications that a small kind of bean was grown at a fairly early date. There is nothing to indicate that root crops were an early feature, but, from the nature of the case, evidence for such crops would not readily survive. It is usually believed, and almost certainly correctly, that grain of some kind preceded all other forms of crops, though there is some difference of opinion as to which was the first grain to be cultivated.

The most important grains grown at the present day are wheat, barley, oats, rye, millet, rice, and maize. The last named is a native of America, and was cultivated nowhere else until introduced from there during the last few centuries. Since civilization in Central America is believed to date from little more than two thousand years ago, we may dismiss maize as being a relatively recent element of civilization. Rice, though it is now grown in some parts of Europe and America, is native to the south-east quarter of Asia; it is characteristic of the monsoon regions. Though evidence has recently come to light of early civilizations in China and India, these cannot be traced very much earlier than 2000 B.C. in the former country, nor quite so early as 3000 B.C. in the latter, while we have much earlier evidence of grain cultivation in the ancient civilizations in the Near East.

A kind of millet (*Panicum colonum*) grows wild in the Sudan, and was used at an early date by the Egyptians; whether they cultivated this grain or merely collected the seeds from the wild plants is, and must remain, uncertain. Another kind of millet, *Panicum miliaceum*, has been found in an early settlement in South Russia and in one of the lake dwellings in Switzerland. It has never been found growing wild, and it is believed to have been native to some part of Asia. Since the earliest evidence of its use dates from after 3000 B.C., it is unlikely that it was the first grain to be grown.

Professor Vavilov tells us that in some parts of the world, rye is a common weed in fields of Emmer, a kind of wheat, and that both grains are harvested together and both sown, as a rule, for the next crop. At higher altitudes, especially in Afghanistan, the rye, which is the hardier crop, tends to grow more successfully than the Emmer, and at great heights the weed entirely supplants the crop. It seems likely that the same thing has occurred in more northerly latitudes, for rye is grown more frequently than wheat in many parts of North Europe.

Oats is a crop that is believed to have been first cultivated in North Europe. Wild oats have a wide distribution and range across Europe and Asia from Galicia, north of the Carpathian Mountains, across Russia and Turkestan to the slopes of the Hindu Kush. They are found as far south as the slopes of the Caucasus and the Kopet Dagh Mountains. It has generally been believed that oats were first cultivated early in the Christian era by Teutonic tribes in the plain of North Germany, for no instances of this crop have been found in the Mediterranean region before the downfall of the Roman Empire. Since, however, Dr. R. C. Clay has recently found oats among other grain in pit dwellings at Fifield Bavant in Wiltshire, which date from between 500 and 400 B.C., we must admit that this grain was grown in the north earlier than had been supposed. Vavilov has pointed out that oats occur as weeds in fields of Emmer in various regions between Persia and the Basque provinces in the Pyrenees. It may be, therefore, that the oats found at Fifield Bavant were not cultivated intentionally, but occurred as weeds in crops of Emmer.

There remain only wheat and barley, and it is impossible at the present moment to decide with certainty to which the priority belongs. In Mesopotamia it was not unusual, even as late as the time of Hammurabi, King of Babylon from 2067 to 2034 B.C., to reckon rents and wages in *gurs* of barley; it is very rare to find wheat used in this way. This might be taken to indicate that for long barley had been the only crop and had become a standard of value. On the other hand, the earliest specimens of grain actually found in Mesopotamia up to the present moment are a kind of wheat. In Egypt it is claimed that barley was cultivated in the earliest days, but, as we shall see in a later chapter, it is not certain that these specimens of barley are any earlier than some grains of wheat found some years later, or that either are as early as the first wheat from Mesopotamia already mentioned. We must leave open the question of the relative age of wheat and barley cultivation until we have made a further exploration of the problem.

Wild barley (*Hordeum spontaneum*) is fairly broadly distributed, for it has been found widely over South-West Asia and has been recorded from Asia Minor, Turkestan, Bokhara, Persia, Northern Afghanistan, and Transcaucasia. It has been found in Palestine as far south as Mar Saba and Ayan Musa, west and east of the Dead Sea, and it has been stated that it occurs also in Arabia Petræa, but this statement needs confirmation. Professor Vavilov has included North Africa, Morocco, and Abyssinia among the countries in which barley grows wild, but this statement needs qualification. He seems to have obtained his data for Abyssinia from Dr. H. V. Harlan, of the United States Department of Agriculture, but the latter has informed the present writer that, though he made a careful search for it at the right time of the year, he failed to find any plants. Though the soil and climate of Morocco are suitable for the growth of wild barley, it does not appear to have been found there, while farther east, in Tripoli, Dr. Taubert in 1887 found a few plants growing wild in Wadi Dernia in Cyrenaica, and Dr. Schweinfurth found others in 1890 at Badia in the province of Marmarica. It seems probable, then, that wild barley at one time grew over a large area in South-West Asia, from Asia Minor to Afghanistan, and spread as far south as the Sinaitic Peninsula; it also crossed into Africa, spreading along a northern strip of that continent almost as far as the confines of Tunisia.

Wild wheat is a much more intricate matter. Botanists recognize a large number of species of wheat and innumerable varieties, but they can all be placed in one of three groups. The first of these is a very small grain, now grown very rarely, for it has little nourishing value; this is called Einkorn. The second is a slightly better type, which will grow at high altitudes and in northerly climates; it is known as Emmer. This was the only kind of wheat grown in the Mediterranean region until the Roman civilization arose in Italy, and no other kind of wheat was grown in Egypt until a few years before the beginning of the Christian era. Most of the wheats now grown, especially in highly civilized areas, belong to the third group; these are generally known as Bread Wheats.

A wild form of Einkorn is found at the present day all over Asia Minor, from the Ægean coast to the borders of Persia and as far south as North Syria. A smaller form is found also in many parts of Greece, such as Argolis, Achaia, Bœotia, and Thessaly; it occurs also in the south of Yugo-Slavia and Bulgaria, in the Crimea, and, so it is said, at the eastern end of the Caucasus Mountains. Its distribution in Europe is mainly confined to mountainous regions draining into the Ægean and Black Seas, though in Yugo-Slavia, where it is a common weed in vineyards, Einkorn has spread up the Vardar Valley to its head, across the divide, and some little way down the valley of the Morava.

Until fairly recently there was some uncertainty as to the area in which Emmer grew wild. Berosus, a Chaldæan priest, who wrote a history of Mesopotamia about 275 B.C., stated that Emmer grew wild in the land of the Babylonians between the Tigris and the Euphrates. In 1787 André Michaux saw what he described as " Spelt wheat " growing wild in Persia, north of Hamadan, and at the beginning of the nineteenth century Olivier found growing on the right bank of the Euphrates, north-west of Anah, " near the camp, in a sort of ravine, wheat, barley, and spelt, which we had already seen many times in Mesopotamia." As no specimens of these grains have been preserved, it is impossible to be certain that they were the wild species and not strays from cultivation. Professor Percival writes: " It is highly probable that the 'spelt' to which Olivier refers was the fragile eared Wild Emmer"; on the other hand, it is possible that this and the spelt found by Michaux were plants of Einkorn, often called 'small spelt.'"

However this may be, the true Wild Emmer was rediscovered in 1906 at Rosh Pinar, at the foot of Jebel Safed in Syria by Aaronsohn, who found it later at Rashey-ya and elsewhere on the slopes of Mount Hermon, as well as on the plateau of Es-Salt, east of the Jordan Valley. He found it growing in crevices of limestone rocks in dry situations between 300 and 500 feet below and over 6,000 feet above the Mediterranean level, usually associated with wild barley and often, in the north, with Wild Einkorn. Specimens of what was believed to be Wild Emmer were collected in 1910 by Theodor Strauss in the mountainous region of Western Persia, near Kerind, between Kermanshah and Bagdad. Professor Percival says that Strauss only found one plant, and that, in his opinion, it might well have been a stray.

Thus, as far as our certain evidence goes, Emmer grows wild only along a strip of country ranging from South Syria to the mountains of Moab, almost all of it east of the Jordan Valley. Though claims have been made for its occurrence farther east, as far as the borders of Persia, it seems possible that some of the plants found were Wild Einkorn or cultivated Emmer escaped from neighbouring fields.

The origin of Bread Wheats is very obscure. No species of this group has ever been found wild, and they are believed to be the products of cultivation. Some years ago Professor Percival suggested that they were hybrids, and this suggestion has received universal assent. He suggested that the parents of the Bread Wheats were the Wild Emmer and some wild grass, either *Ægilops ovata* or *Ægilops cylindrica.* Others believe that it is a hybrid between an *Ægilops* and some wild wheat which is no longer to be found.

Professor Ruggles Gates has recently given very good reasons for believing that the Bread Wheats are the results of crossing Wild Einkorn with Wild Emmer. There is as yet no general agreement on this question, but Professor Ruggles Gates's solution seems the more probable. Where this crossing first took place is uncertain, but it must have occurred somewhere in South-West Asia, possibly in or near North Syria, where both Einkorn and Emmer grow wild. On the other hand, since the earliest known Bread Wheats come from South Russia and Turkestan, it is possible that it was in Transcaucasia that the crossing first took place.

This is all that is known at present about the distribution of wild barley and wheat, and it suggests that the latter grain must first have been cultivated somewhere in South-West Asia, and that barley was first grown either there or in North Africa. Professor Vavilov has, however, made another suggestion, which we must now consider.

Professor Vavilov, as a botanist, naturally attaches more importance to the botanical method of solving this question than to the evidence obtainable from the study of history, archæology, or linguistics, though he admits that these studies are valuable as providing evidence to confirm or modify the conclusions arrived at by the botanical method. He criticizes at some length the botanical method of de Candolle, who published his great work on the origins of cultivated plants in 1882, claiming that recent discoveries as to the number of species and varieties of grain-bearing plants had cast a completely new light on the problem. De Candolle had considered that plants were first cultivated in or near the region in which the wild forms are still to be found. Vavilov claims that this reasoning is unsound, for the wild plants in question may formerly have had a wider range; moreover, the cultivated forms may have been derived from other species or varieties now no longer to be found in a wild state.

Vavilov has referred to a theory, put forward in 1922 by Willis, that species have originated where the greatest number of varieties are now to be found, and in the same way genera have first developed in those regions which now hold the greatest number of species. Accepting this theory as proven, Vavilov claims that a grain-plant was first cultivated where the greatest number of varieties are now grown. He admits, however, that another cause may lead to the presence of a great number of varieties, for these may be found in areas into which culture has penetrated from various directions. Thus he divides the regions in which a great variety of cultivated forms are found into primary centres, in which he believes cultivation began, and into secondary centres into which civilization has been introduced from many sources.

Vavilov's hypothesis, though it has been received with the respect due to its distinguished author, has not yet received general acceptance among British botanists, and has failed to receive the approval of most of the leading British experts on grain-bearing plants. It will be well, however, to examine his conclusions with regard to the first centres of cultivation of barley and wheat, and to see whether the evidence from archæology, history, and linguistics gives them any support, for even Vavilov himself has admitted the value of these sciences as confirmatory tests.

According to Vavilov the greatest number of varieties of barley are grown in Abyssinia, which is especially rich in forms of hulled barley, while another such centre is somewhere in South-Eastern Asia, either in China, Japan, or in the regions adjoining Tibet, such as Nepal. Here some varieties have naked grains, some with short awns and others with no awns, but in their place three-lobed projections. Little is known about the early history of civilization in South-East Asia, but during the last few years a number of village sites have been found in Northern China, stretching from the edge of the Gobi Desert almost to within sight of the Gulf of Pechili. On these sites have been found vast quantities of potsherds, stone implements, and in the most westerly site a few copper arrow-heads. That agriculture was practised by the people of these villages has been inferred, for it is unlikely that people would live in villages and possess large quantities of pottery if they were hunters, collectors, or pastoral folk. The pottery bears a distant resemblance to some found at Anau in Turkestan, and a closer likeness to some discovered by Sir Aurel Stein in Seistan, in East Persia. The inference is that the potter's art was introduced into China through Chinese Turkestan from Russian Turkestan or East Persia, and that with it came the art of agriculture and the knowledge of copper, though the last named was soon forgotten when the people had lost touch with their former homes. The date of these settlements is uncertain, but it is generally believed that they do not date from before 2500 B.C., though a date as early as 3000 B.C. has been suggested. In any case the arts of pot-making and agriculture have clearly been introduced into China from the Near East at a date long subsequent to their discovery in the latter region. The art of agriculture reached Japan, probably from Corea, after 1000 B.C., for up till then the population of those islands were living as collectors by the seashore.

Recent discoveries in India, at Mohenjo-daro in Sind, and at Harappa in the Punjab, have shown us that civilization entered the peninsula at a much earlier date than had been supposed. The discovery of pottery, similar to that found at these two sites, at Nal in Baluchistan, suggests that this civilization entered the Indus valley from the west, perhaps ultimately from Seistan or Turkestan. There is also reason for thinking that the people of Mohenjo-daro had trade relations with the Sumerian cities of Mesopotamia, as early as 2500 B.C., if not before. This civilization is said to go back to 3000 B.C. or even earlier, but the evidence available at the moment does not seem to indicate with certainty a date much earlier than 2600 B.C. Be this as it may, we have no reason for supposing that the arts of agriculture and pot-making in the Indus Valley are nearly so old as they are known to be in the Near East.

It is clear from the archæological evidence cited above that the art of agriculture entered Eastern Asia by two routes, one through Mongolia and North-West China and the other through North-West India. It is likely, therefore, that South-Eastern Asia received its knowledge of agriculture from two sources, and this may account for the great variety of barleys cultivated there to-day. One may suggest, therefore, that South-Eastern Asia is one of the secondary centres that Vavilov has described.

In Abyssinia the case is different. Here we have absolutely no evidence of early settlements, and from what we know of the early history of Egypt, which will be discussed in the next chapter, it seems unlikely that civilization was earlier in that mountainous country than in the Nile Valley. All our evidence seems to show that in North-East Africa civilization spread from the north to the south, until ultimately it reached the Sudan and Abyssinia. On the other hand, the Abyssinians of to-day speak a Semitic language, which shows us that some of the people have come over, at a relatively late date, from the Arabian side of the Red Sea. These newcomers doubtless brought some elements of civilization with them. Thus Abyssinia, like South-East Asia, has received its culture from two directions, and the reason why so many varieties of barley are grown there to-day may be that it is a secondary centre in the sense that Vavilov has defined it.

When we come to wheats we find Vavilov's hypothesis scarcely more in accord with the archæological evidence. It is true that he suggests that Asia Minor is the region in which Einkorn was first grown, a conclusion which we have reached on other grounds. He finds the greatest variety of cultivated Emmers on the shores of the Mediterranean, especially in the North African coast lands, and states as special centres Abyssinia, Algeria, and Greece. The objections to Abyssinia as the first centre of the cultivation of Emmer are identical with those already cited in the case of barley. We have no evidence of true civilization, with pottery and agriculture, in Algeria before the Iron Age, and it seems probable that these arts were first introduced into that country by the Phœnicians about 700 B.C., or conceivably a few centuries earlier. In Greece the first grain to be cultivated seems to have been Einkorn, though this has not been established with certainty, and about 2600 B.C. Bread Wheats were introduced into Thessaly, apparently from the South Russian plain, and thence spread over the greater part of the mainland of Greece. It is possible that Emmer was introduced into Crete from Egypt at an early date, and may have been carried thence to the Cyclades and from there to the plain of Argolis, but of this we have no direct evidence. We cannot be sure that Emmer was grown on the Greek mainland until much later. One thing is clear—namely, that there was little if any knowledge of agriculture in Greece until about 3000 B.C., or perhaps a few centuries earlier. In Crete, it is true, civilization goes back earlier still, but it reached there first from Asia Minor, where Einkorn grows wild and where even Vavilov admits it was first cultivated; it was not until about 3400 B.C. that a new people reached Crete from Egypt, whence they may have brought Emmer. Archæological evidence, therefore, is strongly against the hypothesis that Emmer was first cultivated in Abyssinia, Algeria, or Greece.

We have still to discuss the place of origin of the Bread Wheats. Vavilov suggests that the region in which they were first cultivated was in South-West Asia, a view that is in general agreement with what we have already suggested. When, however, he comes to particularize, our views are at variance. He finds the greatest number of cultivated varieties in Eastern Afghanistan, the next largest number in Persia, and the third in Transcaucasia. The last-named region, since it has, he believes, received elements of culture from Turkestan and Armenia, he classes as a secondary centre. It is true that Afghanistan has been little explored from the archæological standpoint, and it would be unwise to assert that because no early settlements have been found there that none existed. On the other hand, the beginnings of agriculture, as we shall see in a later chapter, go back to so early a date that considerable remains of the last Ice Age must still have been left on the Himalayan plateau, and the climate of the mountainous parts of Afghanistan would have been too severe to permit of the cultivation of Bread Wheats, which are less hardy than Einkorn or even than Emmer. It seems, then, improbable that Afghanistan was the region in which they were first cultivated.

Of Persia it is not so easy to speak. There is much reason for thinking that four or five thousand years ago the Persian plateau was not so dry as it is now. Pottery, believed to date from a very early age, has been found on several sites; that discovered by Sir Aurel Stein in Seistan has been already mentioned. Moreover, Susa, at which the first settlement is one of the earliest, if not actually the earliest, agricultural village known, is within the boundaries of Persia, though geographically within the Mesopotamian region. That the Bread Wheats were first cultivated in Persia is a possibility; time will show whether it is a probability.

Vavilov has suggested that Transcaucasia was a secondary centre for the cultivation of Bread Wheats. Archæological evidence, on the other hand, points to the possibility of it having been a primary centre. The earliest positive evidence of Bread Wheats that we possess comes from Thessaly and the Danube basin, in both cases just after the arrival of new people, who are believed to have come there from the Black Earth Lands of South Russia. Bread Wheat has been found in a settlement near Kiev of a slightly later date. Again, Bread Wheat was found in the lowest layer at Anau in Turkestan, which probably dates from much the same time. We have evidence that these two areas were in touch with one another, though this evidence does not go back to the earliest phase of either culture; there are many people, however, who argue from the resemblances between the pottery from both sites that the civilizations of both regions are related and have come from a common centre. There are some reasons for believing that Transcaucasia was the region from which both the Black Earth Lands of Russia and the early people of Anau obtained the elements of their civilization. It seems probable, then, that Transcaucasia was not a secondary centre, as Vavilov has suggested, but the primary centre from which first spread the cultivation of the Bread Wheats.

It will thus be seen that in the light of archæological evidence the majority of the centres suggested by Vavilov seem unlikely to have been the areas in which grain was first grown. It is too soon to speak with certainty, but, on the evidence available at present, it seems probable that wheat was first grown somewhere in South-Western Asia, Einkorn in Asia Minor, probably near its eastern end, Emmer in North Syria or perhaps a little farther north, and the Bread

Wheats in Transcaucasia or perhaps on the northern slopes of the Armenian Mountains. The problem of barley is more obscure, and it will be well to avoid suggesting any precise locality until we have examined the respective claims of Africa and Asia.

CHAPTER III

THE CASE FOR AFRICA

There is in England a school of thought which claims that all good things have at one time or another come out of Egypt, and especially that there was corn in Egypt before that commodity existed elsewhere. Since no form of wheat has been found growing wild in Africa, these writers make no claim that this grain was first cultivated in Egypt, but they maintain that barley was grown by the Nile before agriculture started elsewhere, and that thence the idea passed to Asia, where wheat was cultivated as well, and whence the superior grain was introduced into Egypt. The views of this school of thought have not received general acceptance, but it must be admitted that, since barley has been found growing wild in North Africa, and has been discovered in very early graves in Egypt, there is nothing impossible in their contention. The question of priority between the two continents needs very careful examination, and it is not easy at the present moment to come to a positive conclusion. We must, however, discuss in detail all the instances in which grain has been found in early deposits in that country.

It was in the year 1899 that the late Mrs. Phœbe Hearst entrusted to Dr. George A. Reisner the organization and direction of an Egyptian expedition. Having obtained the necessary permission from the Department of Antiquities, Dr. Reisner went to Naga-ed-Dêr, in Upper Egypt, on February 1, 1901. From December, 1901, to March, 1903, under Dr. Reisner's direction, Mr. Lythgoe explored a very early cemetery, which is known as the "predynastic cemetery, 7000," because the graves found in it were given numbers beginning with 7001. In the spring of 1902, at the request of Mr. Quibell, Dr. Reisner offered to Dr. Elliot Smith, who then held an appointment at Cairo, all the bodies found in this cemetery, which, owing to the condition in which they were found, were particularly interesting.

Professor Elliot Smith, referring to these bodies some years later, wrote: "From the stomachs and intestines of these prehistoric people I was able to recover large quantities of food materials—in fact, the last meals eaten before death—which Dr. Fritz Netolitzsky, of Czernowitz, kindly undertook to examine. After years of most laborious and highly skilled investigation, he has been able to discover not only the precise nature of the prehistoric diet, but also something of the mode of preparation of the food for consumption. Almost every sample contained husks of barley."

This information was received by Elliot Smith, so he informed the author in a letter from Netolitzsky, who, however, published subsequently two papers describing the contents of these stomachs. By this time he seems to have grown more cautious and to have doubted his earlier determination, for in one paper he says that, while there were glumes in almost all the bodies examined, these glumes could not be identified. The grain, he said, had an ear with a brittle axis and the glumes closely attached to the grain, but he was uncertain whether the grain was wheat or barley. In the other paper he refers merely to grain. He cites materials from thirteen graves; remains of grain were found in seven of these.

Netolitzsky was not, however, satisfied to leave the matter undetermined, and set a pupil to work on the material. The pupil, Dr. Hedwig Gherazim, finally proved that the glumes were those of barley. We may, therefore, rest satisfied that during what are called "predynastic times" the inhabitants of Upper Egypt used barley for food and presumably cultivated the plant. Professor Percival has, however, pointed out that the evidence cited by Netolitzsky and Dr. Gherazim does not prove that wheat was not eaten as well, for, he writes, "in barley the husks (glumes) are closely adherent to the grains, and portions of them are consequently consumed with them, whereas in wheat the husks or glumes are free from the grains and must be removed before the latter can be used as food."

Before we can appreciate the importance of this evidence, we must be clear what is meant by "predynastic times." The early native authorities on Egyptian history, who wrote during the first centuries of the Christian era, had much to say of a traditional monarch, whom they called Menes, and who was the first to unite Egypt into one kingdom. From the time of Menes until the conquest of Egypt by Alexander the Great a large number of kings had ruled the country. These we considered to have belonged to thirty dynasties, and the time during which they ruled is known as the Dynastic period. Monuments and inscriptions of most of these dynastic kings have been discovered, though the actual name of Menes has not been found. The deeds traditionally attributed to him seem to have been performed by the first two kings of the First Dynasty, Narmer and Aha. There is still considerable difference of opinion as to the date of Menes, and the various theories current will be discussed in a later chapter. Although there are two relatively blank phases of short duration, a continuous history of the dynastic period has been compiled from the evidence of the monuments.

During the last thirty years a large number of graves have been found, the contents of which can be shown to date from before the dynastic period. These are known as Predynastic. There have also been found a few remains of huts, the pottery from which shows that they, too, are predynastic. Except during the last stages of the predynastic period no writing has been found nor have we any lists of kings; just at its close, however, a few simple signs occur, graven on slate palettes and other objects, and a few names of local kings have been found. This almost entire absence of the names of kings and of inscriptions makes it impossible to date in years the objects found in predynastic cemeteries, or to estimate the length of the period as a whole. All we can be sure is that the period came to an end with the accession of Menes as the first king of a united Egypt, an event which, as we have seen, ushered in the dynastic period.

Though we cannot estimate the length of predynastic times, or form for it what is known as a positive chronology, an ingenious device, invented by Sir Flinders Petrie in 1901, enables us to form a relative chronology, and to place the various graves and huts in a correct succession in time, though we cannot yet measure in years the intervals that elapsed between each of them. Petrie has shown that the different types of pots found in the predynastic graves can be arranged in sequences, showing progressive stages of development, and on this principle he has divided predynastic times into a series of short periods, which he has called Sequence Dates. The earliest of these, when the graves contained only a single primitive black-topped pot, he has called sequence date 30, leaving the other twenty-nine numbers blank in case earlier graves should be found. The latest graves of the Second Dynasty come in his sequence date 100, while Menes, the first king of the First Dynasty, falls into sequence date 79. Thus the predynastic period is covered by the sequence dates 30-78. Further than this, he finds that the whole predynastic period is capable of being divided into three great sub-periods, each beginning with the introduction of several new elements of civilization. These he has termed Early, Middle, and Late, and he considers the Early as including sequence dates 30-39, the Middle 40-59, and the Late 60-78. Except for a slight criticism recently made by Dr. H. Frankfort, who has doubted the existence of sequence date 30, believing the graves with one pot only to be poor graves of sequence date 31, this system of Petrie's has received almost universal approval. It has been in use now for more than a quarter of a century and has been found to work admirably.

During the early predynastic period, from sequence date 30 to 39, the civilization of Egypt is believed to have been free from foreign influences. Various types of pottery were in use, of which a red ware with black tops, commonly called black-topped ware, was the most characteristic; the people at this time used maces with disc-shaped heads. The forms of the pottery and of the mace-heads changed somewhat in each sequence date, but throughout this period we see an orderly evolution of the same elements.

With sequence date 40, however, came a sudden change. An entirely new type of pottery with wavy handles made its appearance, and a new form of mace-head, not derived from the earlier type but with a pear-shaped head, came suddenly into use. The wavy-handled pots are believed to have been brought into Egypt from Palestine, though positive evidence for this is for the moment lacking. This is not so in the case of the pear-shaped mace-heads. These occur not infrequently in very early deposits in Palestine, and a fine example has recently been found with very early associations on the site of Mizpah. Such mace-heads are common in Mesopotamia throughout nearly all periods, and they have been found in some of the very earliest deposits, such as those at Tell-el-Obeid near Ur and at Abu-Shahrain, the ancient Eridu. It is uncertain in what region this type first originated, but it has been suggested that mace-heads of this form were first used in Syria and spread thence to Mesopotamia and Palestine, and that they passed from the latter country into Egypt in sequence date 40.

The sudden arrival of the pear-shaped mace-heads and the wavy-handled pots in sequence date 40 has, with good reason, been thought to indicate that at this time influences were entering Egypt from Palestine and perhaps ultimately from Syria; it is even possible that their presence may indicate the arrival in considerable numbers of a new people, bringing with them a fresh and perhaps superior civilization. It is possible, therefore, that the practice of agriculture and the cultivation of both wheat and barley were introduced at this time into Egypt from Asia. All depends on the reply to the question : to what sequence date belong the graves found by Reisner in cemetery 7000 at Naga-ed-Dêr, especially the graves containing the bodies in whose intestines Elliot Smith found the remains which Netolitzsky and Dr. Gherazim identified as husks of barley? Before we attempt to answer this question, we must see what other evidence there is for the presence of grain in Egypt during predynastic times.

In his great work on grain in Babylonia, in which he has approached the subject from the linguistic side, Dr. Hrozny has stated that grains of barley and Emmer were found " with contracted burials at Silsileh without trace of copper or bronze." No detailed account of this discovery has been published, and de Morgan, who gave a brief description of this cemetery, makes no mention of grain having been found there. That grain was actually discovered there, or, to be more accurate, between Kawamil and Silsileh, by Legrain and Lampre in 1896-7 is clear from a statement made by Dr. Schultz, to whom samples of the grain had been sent. Schultz said that the grain found there was barley, *Hordeum vulgare*, and not Emmer, as had been thought.

Unfortunately we do not know the exact age of these burials, for no descriptions of the graves or their contents have been published. The absence of metal is no proof of a very early date, for copper has been found in graves of sequence date 30, and quite recently in Badarian graves that are thought to be earlier still, while it is often absent in graves of poor people of a much later date. This discovery, in itself of very great importance, does not help us in our inquiry and will not solve our problem until we can learn to what sequence date to attribute the graves in which this grain was found.

There are three other cases of the discovery of grain in predynastic Egypt which will be more helpful. In the winter of 1912-13, Professor T. Eric Peet was excavating at Abydos in Upper Egypt. Here he found a range of large pots, which had been used as a kiln in which to dry grain. In these pots he found small black masses or cakes of carbonized organic matter, which were full of grains. Some of these grains were brought back to England and subjected to a careful examination by a botanist, who described them as wheat. He suggested that these were grains of a Bread Wheat, though it is generally believed that this determination was mistaken, for Bread Wheats have not been found in Egypt before the time of the Roman occupation and until then Emmer seems to have been the only wheat cultivated.

Professor Peet had no hesitation in pronouncing these kilns to date from predynastic times, but there was insufficient evidence to show to what section of that period they should be attributed. A very similar series of pots was found later on at no great distance from the former, and, though they contained no remains of carbonized grain, a number of potsherds were found lying close by, which served to give an approximate date to the kiln. These showed that the second kiln dated from the middle predynastic period, though probably to a relatively late phase of that period. It is practically certain that the kiln containing the grain was almost, if not quite, contemporary.

More recently Miss Caton-Thompson has found some grain, which has been identified by Professor Percival as Emmer, at the bottom of a ruined hut at Badari in the Assiût district. The pottery in this hut was so rude that it was quite useless for the purpose of dating the building, but after the hut had been destroyed it was covered by a layer of rubbish containing many fragments of decorated pottery, which can be attributed with fair certainty to the latter part of the Middle Predynastic period. While one must speak with due reserve, it seems probable that this hut dates from the first half of that period, perhaps from its very beginning.

A still more important piece of evidence comes from the same district, from an early settlement at Hemamieh, between Qau and Badari, explored recently by Mr. Guy Brunton. Judging by the pottery found, which is rough and not very typical, the settlement would date, according to Mr. Brunton, from between sequence dates 37 and 44. "A slate, a disc-shaped mace-head, and a stone vase," he wrote to the author, "would be all around sequence date 40." The grain was found in a rough cooking-pot, which is quite undatable, and it has been identified by Professor Percival as Emmer.

Here, then, we have two cases of wheat, one of them undoubtedly Emmer, dating from the Middle Predynastic period, one of them clearly from the early part of that period, and a third case, also Emmer, dating from sequence date 40, the very beginning of that period, though conceivably a trifle earlier. This evidence, taken as a whole, suggests that Emmer, together with wavy handled pots and pear-shaped mace-heads, was introduced into Egypt from Palestine, about sequence date 40, by people who introduced those new elements of civilization that distinguish the Middle from the Early Predynastic period. Whether the practice of cultivating barley was introduced at the same time, or was known earlier to the inhabitants by the Nile, is a question that must now engage our attention.

It is very unfortunate that no full description has been published of the contents of those graves which Legrain and Lampre found near Silsileh, for did we know the forms of the pots and other objects found with the grains of barley, we could decide whether the remains belonged to the Early or Middle Predynastic periods. As we have seen, the bare statement that no metal was found in them gives us no clue to the date.

We are in the same position when we come to the grain found in the stomachs of the people buried at Naga-ed-Dêr. Although cemetery 7000 was excavated in the winters of 1901-2 and 1902-3, no full account of the grave contents has yet been published, though a brief general statement appeared in an account of a later expedition to Nubia, which was published in 1910. In this report Dr. Reisner suggested a triple division of predynastic times into Early, Middle, and Late periods, based upon the type of grave used. He made no attempt to bring his classification into line with that proposed some years earlier by Sir Flinders Petrie, and it is understood that he is one of the few Egyptologists who decline to accept the system of sequence dates. We cannot be sure, therefore, that the Early, Middle, and Late Predynastic periods of Reisner are the same as those defined by Petrie.

In his report on the Nubian expedition, Reisner stated that the graves in cemetery 7000 at Naga-ed-Dêr belonged to his Early and Middle Predynastic periods, and in 1911 Professor Elliot Smith stated that the graves in which barley was found belonged, according to Reisner, to his Early period. If we could be sure that the three periods of Reisner were even approximately the same as those of Petrie, we might feel satisfied that barley was used at Naga-ed-Dêr before sequence date 40, when the new influences reached Egypt from Palestine. Unfortunately we cannot be sure of this, and until a full account of the contents of the graves of cemetery 7000 has been published the question must be left open.

Let us now endeavour to sum up, as far as circumstances permit, the conclusions at which we have arrived as to the early cultivation of grain on the African continent. If we were to agree with the conclusions of Vavilov, we should have to admit that Emmer grew wild and was first cultivated in Abyssinia and perhaps in Algeria. On the other hand, no Wild Emmer has been found growing in any part of Africa, and from what we know of the two regions in question it seems highly improbable that in either was grain cultivated at an early date. Moreover, although we have found evidence in three cases that wheat of some kind—and in two of these the grain was certainly Emmer—was grown in Egypt in Predynastic times, in all three cases it is clear that the grain belonged to the Middle Predynastic period, and is not earlier than sequence date 40, when we have other reasons for believing that new influences, brought by fresh people, entered Egypt from Palestine. This evidence seems to point definitely to the conclusion that Emmer, and other forms of wheat as well, were first cultivated in some part of Asia.

The question of barley is not so clear. Since Wild Barley has been found growing in two places in Tripoli, we cannot deny the possibility that it once grew wild in the desert behind Alexandria, where the Bedouin still raise large crops of the cultivated species. It may even have grown in suitable spots on the hillsides on either side of the Nile Valley. Considering what large areas still remain uncultivated in Abyssinia, it is strange that Wild Barley cannot now be found in that country if, as Vavilov has claimed, it once grew wild in that region. That in predynastic times the Egyptians cultivated barley is clear from the evidence obtained from near Silsileh and at Naga-ed-Dêr, but, owing to the difficulty in dating the graves from which these grains were obtained, it is impossible at the moment to be certain whether or not these remains belong to a time before or after sequence date 40, and so whether or not the Egyptians made an independent discovery of the art of agriculture.

CHAPTER IV

THE CASE FOR ASIA

It has been known for many years that the part of Mesopotamia lying nearest to the Persian Gulf was known in early days as Sumer. Here were a number of flourishing cities inhabited by the Sumerians, whose language is known to us from many inscriptions, written with wedge-shaped characters on small clay tablets. As we shall see later, the Sumerians were probably not the first inhabitants of that region, but they had founded cities there at a very early date. From time to time wandering pastoral tribes from the desert made settlements in the rich lands in the valley, and sometimes were able for a time to bring all, or at any rate some, of the Sumerian cities under their rule. These empires founded by the pastoral folk seldom lasted much more than a century before the Sumerian cities succeeded in re-establishing their independence.

It was, however, soon after 2200 B.C. that one of these pastoral tribes, the Amurru, or the peoples from the west, established a kingdom with its headquarters at Babylon, which had hitherto been an unimportant town, although one of peculiar sanctity. These Amurru—a name better known in later days as the Amorites—spoke a Semitic tongue; that is to say, a language closely allied to Hebrew, Phœnician, and Arabic. They soon established their rule over many Sumerian cities, and when a hundred years had passed the last of these was included in the empire of the Semitic conquerors, who are known as the First Babylonian Dynasty.

The Sumerians, who had enjoyed a far higher civilization than that possessed by their conquerors, naturally resented the loss of their freedom, and began to compile short histories of the glorious times during which they had been independent. These short histories took the form of lists of kings, with the lengths of their reigns, placed under the headings of the successive dynasties that had ruled in Mesopotamia, together with an occasional mention of some important event. Several such lists of kings have been found, many of them in a fragmentary and all in an imperfect condition. The best preserved of these is that known as the Weld-Blundell prism, now in the Ashmolean Museum at Oxford. Though there are slight differences in detail between these lists, they are all in general agreement, and it is admitted that they give a substantially accurate account of the rulers of the cities in Mesopotamia for a period of nearly two thousand years.

All these lists begin with about eleven monarchs, each of whom is said to have ruled in a different city, the sites of some of which have not yet been identified. One of these cities was Eridu, the site of which is called Abu-Shahrain, where, as we have seen, evidence of early agriculture has been found. The last king, who reigned at Suruppak, is called by Berosus Xithuthros. Then came a long period, described as the flood, from which Xithuthros escaped in a boat, and then a succession of dynasties, of which the first three were the First Dynasty of Kish, the First Dynasty of Erech, and the First Dynasty of Ur. The text of the document, which relates to these early periods, has evidently become corrupt, for the antediluvian monarchs are said to have reigned for an enormous time, the lengths of some reigns exceeding 100,000 years. The flood, too, is said to have lasted for an even longer time, and the kings of the two next dynasties also reigned for impossibly long periods. It is only when we get to the First Dynasty of Ur that we meet with reigns of reasonable length. Even the reign of the first king of Ur, Mes-anni-padda, is given as eighty years, which is an impossible length for the founder of a dynasty. This, however, is now capable of explanation, for a few years ago, while digging at Tell-el-Obeid, about four miles from Ur, Dr. H. R. Hall found an inscribed marble tablet, stating that A-anni-padda, King of Ur, son of Mes-anni-padda, King of Ur, had erected a temple to Nin-Khursag, the Moon Goddess. Now, A-anni-padda's name does not occur in the lists of kings, and it is believed that the eighty years ascribed to Mes-anni-padda included also the reign of A-anni-padda, his son. It is, therefore, agreed that from the First Dynasty of Ur the list of kings may be considered as an historical document.

For some time it was thought that no reliance could be placed upon the accounts of the earlier dynasties, whose kings were said to have had such incredibly long reigns. Lately, however, on the site of Kish there has been discovered a layer, the remains from which are clearly much older than those belonging to the First Dynasty of Ur, and during the last two years at Ur itself Mr. Woolley has found graves containing elaborate gold ornaments and weapons, as well as many other evidences of a high civilization, as much as twelve feet and more below the foundations of buildings which are known to have been erected under the First Dynasty of that city. The First Dynasty of Kish has now become an established fact, though it is clear that the lengths of its kings' reigns have been grossly exaggerated; we may conclude, too, that the intervening dynasty of Erech may also be considered as historical.

An interesting point has quite recently come to light and has lately been made public by Professor Langdon. This is that the people of Kish were not Sumerians, but the folk who were later known as Elamites. At Erech the kings of the First Dynasty had true

Sumerian names, and it seems likely that the rise of this dynasty to power indicates the first time at which the Sumerians became of political importance in Mesopotamia.

Making due allowance for the corruption of the text and the legendary nature of the earlier portions, we may assume that at a very early date there were cities, or probably villages, in the plain of Mesopotamia, each governed by a king or head-man. Then occurred a period in which the annual floods of the Tigris and Euphrates were so extensive that it became impossible to cultivate the low-lying lands, and the plain was abandoned. This period may well have lasted for several centuries. Later on, as the spring floods declined, some people from the north settled at Kish, and made themselves masters of the surrounding region; these spoke the language later known as Elamite. A little later the Sumerians arrived from the south-east, probably by sea, and founded cities by the coast, but soon came under the domination of the Elamites of Kish. After a time the *patesi,* or head-man, of Erech gained his independence and brought other cities under his rule, and the leadership in the valley remained Sumerian until Mes-anni-padda of Ur established his rule over the whole region, which his descendants governed for several generations.

After this brief summary of early Mesopotamian history, we must return to the site of Susa, which lies just outside the plain at the foot of the Zagros Mountains and within the kingdom of Persia. Here M. de Morgan found a number of superimposed layers, the two lowest of which concern us here. In the lowest layer, usually called Susa I., he found quantities of fragments of a very thin type of pottery, painted in dark designs on a pale ground. In graves containing similar pottery he found copper axes and traces of woven linen. It is said that stone corn-grinders were found in this bottom layer, but all the bones found were said by experts to have been those of wild animals, so it is believed that none had been domesticated. Above this layer were many feet of soil, in which no pottery or other remains were found, and above this layer remains of another settlement known as Susa II. In this upper layer were found, amongst other things, fragments of pots, differing in shape from those of Susa I., and decorated in several colours; this is known as the polychrome ware of Susa II.

M. Pottier, who first reported on these wares, while admitting that an interval had elapsed between the two settlements, maintained that the polychrome ware of Susa II. was derived from the thin painted ware of Susa I. Recently Dr. Frankfort, who made a careful study of the whole question, came to the conclusion that the two wares were quite distinct and had no connection with one another. Soon after Frankfort's paper had appeared, Professor Langdon reported a discovery which suggests that the truth lies between these two points of view.

It was in 1926 that Langdon started exploring the site of a deserted village at Jemdet Nasr, some sixteen miles north-east of the site of Kish. In this village, which had been destroyed at a very early date and never afterwards occupied, he found a vast quantity of polychrome pottery, decorated in a style somewhat resembling that from Susa II., but in shape more resembling the pots from Susa I. This village seems to have existed at some time during the interval that elapsed between the two first settlements at Susa, and it seems clear that the Jemdet Nasr pottery, and ultimately that of Susa II., had been derived from some ware very like, and doubtless related to, that of Susa I. In some polychrome pots at Jemdet Nasr, Langdon found a quantity of grain, and the following year he found pots of the identical ware at Kish, in the layer which he had shown to belong to the First Dynasty of that city.

Now, a number of objects had been found in buildings of the First Dynasty of Ur, resembling those of Susa II. sufficiently nearly to suggest that the two deposits were roughly, if not accurately, contemporary. The ware of Jemdet Nasr, intermediate between that of Susa I. and Susa II., was found in deposits of the First Dynasty of Kish, so Susa I. must belong to a still earlier period. Since the First Dynasty of Kish was the first after the period of floods, it seems probable that Susa I. was earlier than that catastrophe, and since the village stood very little raised above the River Kerkha, which ran close to its walls, it is tempting to believe that the spring floods of that river, rising for a period of years to unprecedented heights, and thus making the cultivation of the alluvial lands impossible, was the cause that led to the abandonment of the first village on that site. We can, however, test this by examining the evidence from other Mesopotamian sites.

At several spots in Mesopotamia there have been found fragments of pottery so closely resembling those from Susa I. that it is agreed that they were roughly contemporary and made by the same or closely allied peoples. It will be sufficient for our purpose to refer to two of these sites, both of which have already been mentioned—Tell-el-Obeid, about four miles from Ur, and Abu-Shahrain, the site of the ancient Eridu. At Tell-el-Obeid these fragments were found under circumstances which convinced Dr. Hall, who found them, that they dated from a time long prior to the erection of the temple to Nin-Khursag by A-annipadda, the second king of the First Dynasty of Ur. Along with the potsherds were some rude tools which appeared to have been designed for agricultural operations. At Abu-Shahrain Mr. Campbell-Thompson found large quantities of similar pottery, together with stone hoes and sickles, as well as corn-grinders. It is clear from this evidence that the people who made the fine painted pottery found at Tell-el-Obeid and Abu-Shahrain were cultivators of grain, though of what grain we do not know, and that they lived long before the First Dynasty of Ur. Mr. Woolley has dug deep below the buildings at Ur erected during its First Dynasty and has found no signs of this painted ware, and it seems to be absent from that site. We can only suppose that, as in the case of Susa I., the fine painted ware from Tell-el-Obeid and Abu-Shahrain dates from before the period of floods mentioned in the lists of kings, the catastrophe which gave rise to the stories of Xithuthros, who escaped from Suruppak in a boat, and of Noah, who escaped in an ark. This view receives further support from the fact that Eridu was the seat of one of the antediluvian monarchies, and was never of importance in later times. Thus we are led irresistibly to the conclusion that grain was cultivated in Mesopotamia, in the plain of Shinar or Sumer, before the land was overtaken by the series of floods, the story of which has come down to us as Noah's Deluge.

Though no grain has been found on these antediluvian sites along with the thin painted pottery, and though we are uncertain whether these early people grew wheat or barley or both, we have some direct evidence as to the nature of the crops raised by the Elamites who dwelt in Mesopotamia during the rule of the First Dynasty of Kish. We have seen that at Jemdet Nasr Professor Langdon found a number of polychrome vases almost identical with some that he found later in the lowest layer at Kish, and that in one of these he found a quantity of grain. This grain throws considerable light upon the early agriculture of Mesopotamia, and will help us still further when botanists are agreed on the determination of the species. Four samples were made up from the grain found at Jemdet Nasr and were submitted to four specialists, three in England, and one in America. Three of these gave independent opinions as to the species represented, and, though all agreed that it was some kind of wheat, each of these specialists diagnosed it as a different species. Two of them, one in England and the other in America, pronounced the grain to be a form of Bread Wheat, though they differed as to the species, while the third pronounced it to be Emmer.

We can thus be sure that wheat of some kind was cultivated, and had probably been grown for long, in Mesopotamia during the time of the First Dynasty of Kish, not long after the period of floods, but we cannot tell yet whether this wheat was Emmer, which grows wild in North Syria, Palestine, and Transjordania, or whether it was some kind of Bread Wheat, which, as we have seen, appears to be a hybrid, first grown, so we believe, either in Transcaucasia or on the northern slopes of the Armenian mountains.

Though we are unable to probe this question any deeper, or to search any farther back into the misty past, by means of direct evidence, it may, nevertheless, be worth while to pursue the inquiry further by means of inference and argument. We have seen that at all the earliest sites on which grain was grown the people made and used pottery, lived in settled villages, while at Susa, at any rate, they had woven linen and weapons or tools of copper; this metal from the first settlement at Susa has recently been analyzed and has been found to be practically pure copper, with less than one per cent. of impurities, while in all other known early examples a number of impurities, often amounting to 5 or 6 per cent., have been found. From these facts we may conclude that along with agriculture the potter's art, the textile industry, and the art of metallurgy were also practised, and it is difficult to say which was discovered first.

Dr. Frankfort, who has made a very close study of the pottery of the Near East, was of opinion that the potter's art reached Susa from the north-east, probably from North Syria or somewhere in that part of the world. More recently he has pointed out that in very early times there were three distinct regions, each producing a different type of pottery. These, he thinks, were: Persia, including the valley of the Euphrates, the first; Asia Minor, the second; and a region embracing Syria, Palestine, and Egypt, the third. To these we might add another, perhaps more hypothetical—namely, Transcaucasia, whence the potter's art seems to have spread westward to the Black Earth Lands of South Russia, and eastwards to the region around Anau in Turkestan. It is not unreasonable to suggest that the potter's art, and perhaps agriculture and metallurgy, first arose somewhere near the spot where these four regions most nearly approach one another.

At the point where the Euphrates runs nearest to the Mediterranean Sea stands the town of Jerablus, and this is approached from Alexandretta or Iskanderoon, a little port on the North Syrian coast, by an easy route through Aleppo. The Bagdad railway follows this ancient route, which connected Mesopotamia with the islands of the Mediterranean as early as the time of Sargon of Agade, who ruled his extensive empire about 2700 B.C. The wealth of Antioch, where men were first called Christians, arose from the fact that this city of the Seleucids upon the River Orontes commanded that trade route, and earlier still, in the time of Tut-ankh-amen, Hittite monarchs grew rich from the tolls raised upon this trade, when the city of Karchemish occupied the site of Jerablus.

A little above Jerablus the River Euphrates emerges from the mountainous country that forms the southern portion of the Armenian highlands, and for several hundred miles before it leaves the mountains its course runs from north to south. Halfway along this straight length, only a few miles to the east, rises the most westerly tributary of the Tigris. Just halfway between the head waters of this tributary and the main stream of the Euphrates is a deposit of native copper, which is worked at the present day, and is one of the few rich deposits of pure copper known to exist in this part of the Old World. This spot is just the centre from which diverge the four different pottery regions mentioned above, and it is tempting to believe that these early potters discovered this deposit, and with it the art of metallurgy. It is quite possible that the singularly pure copper used by the people of Susa I. was derived from this source.

If the potter's art and the first working of metals arose somewhere along this reach of the Euphrates, it is possible also that grain was first grown in or around the same region. Wild Barley grows here on the hillsides, as does Wild Einkorn, and it is quite possible that Wild Emmer, only found in recent years a few hundred miles to the south, may have extended in earlier times as far north as this. Moreover, if Professor Ruggles Gates is right, and the Bread Wheats originated in a cross between Einkorn and Emmer, these may have arisen here, too, and spread from this part northwards to Transcaucasia, as well as south-eastwards to Jemdet Nasr, if indeed the grain found there turns out really to be a Bread Wheat. This region, too, must have been near the spot known to early legend as the Garden of Eden, through which flowed the Euphrates and three of its tributaries.

All this is, however, in the nature of surmise, and we must not look upon such a hypothetical centre of civilization as more than a plausible suggestion. Nevertheless, this area seems to offer all the conditions that appear to be needed in the present state of our knowledge. Two other possibilities, however, must be considered.

Professor Langdon has recently shown that the people who lived under the First Dynasty of Kish were Elamites, and the same is consequently true of the wheat growers with the painted pots of Jemdet Nasr. It would seem that the antediluvian makers of the thin painted pots of Tell-el-Obeid and Abu-Shahrain, as well as of the first village on the site of Susa, were a group of the same people, who entered Mesopotamia earlier but were driven away by the excessive spring floods. Recently Professor Langdon has suggested that these Elamites came from the north, probably from Turkestan, where, he believes, there was a very early civilization, which gave rise also to the settlement at Anau, the early cities in Sind and the Punjab and the villages with the painted pottery recently discovered in China. If agriculture arose in the east of Turkestan or in the adjacent mountain country of Afghanistan, this would corroborate the hypothesis of Professor Vavilov that Bread Wheats were first cultivated in the latter region. On the other hand the settlement at Anau, believed by its discoverer to have arisen between 8000 and 7000 B.C., is now thought by most authorities to have begun little, if at all, before 3000 B.C., while the country between Turkestan and Mesopotamia is rugged and mountainous, and a succession of high ranges would have proved an effective barrier to the movements of an agricultural people. It is doubtful whether Professor Langdon's hypothesis will gain any general support.

Lastly let us turn to the testimony of tradition. About fifty years before the beginning of the Christian era Diodorus Siculus was writing his history, in which he gave the story of Osiris and Isis, who were associated in Egypt with the cultivation of corn. In this account he states that Isis discovered wheat, or to be more exact Emmer, and barley growing promiscuously about the country along with other plants and unknown to mankind. In another passage he states that the country in which these plants were found by the goddess was Nysa, which he describes as a high mountain of Phœnicia, far away. It is significant that Mount Hermon, on the slopes of which in 1908 Aaronsohn first found Emmer growing wild, lies about thirty miles inland from the sites of the Phœnician settlements of Tyre and Sidon.

Time will, perhaps, show us which, if any, of these three suggestions is the true solution of our problem; either the first or the last seems the most probable. In any case the balance of evidence seems in favour of the view that wheat was first cultivated at some spot in South-West Asia, in all probability within a few hundred miles of Aleppo. Whether one of the three grains was first cultivated, after which the knowledge spread to the regions in which the others grew wild, or whether, on the other hand, two or three different centres experimented independently with different kinds of wheat, we cannot yet be sure. Since Wild Barley is found more commonly in Asia than in Africa, it is natural to expect that it was first cultivated in the same region in which wheat also was first grown, but, until it can be shown that the predynastic graves in which barley has been found near Silsileh and at Naga-ed-Dêr are later than sequence date 40, we cannot be sure that the dwellers by the banks of the Nile had not made independent experiments in the cultivation of that grain.

CHAPTER V

WHEN DID AGRICULTURE BEGIN?

We have now carried our inquiries as to the region in which agriculture was first practised as far as is possible with the evidence at present available, and we must now turn to the much more difficult problem of attempting to define the date at which grain was first grown. We have discussed at some length the various periods into which the histories of Egypt and Mesopotamia have been divided and the different dynasties that have ruled those lands, but hitherto few dates have been given, since on such points there is still much disagreement among those best able to speak with authority on the subject, and it will be necessary to consider these divergent views on the evidence on which they are based.

It has already been pointed out that the early historians of Egypt recognized thirty successive dynasties of kings since the traditional Menes united under his rule the two provinces of Upper and Lower Egypt, and several lists of kings exist with the lengths of the reigns of each, though these lists are in some respects imperfect. Nevertheless, by a careful study of inscriptions, the true names of the great majority of these kings have been recovered, and in most cases the lengths of their reigns, though occasionally there is some uncertainty, amounting only to a year or two, on the last point. If we had these lists absolutely complete and the lengths of these reigns precisely determined, we could, one would think, reckon backwards to Menes with precision. This, however, is not so. Every king must have reigned for some months, weeks, or at any rate days more or less than an exact number of years, and, unless we know the exact date of the death of each monarch, we are unable to determine these fractions, which mount up to a respectable figure during thirty dynasties, some of which include a considerable number of kings. This is our first possible source of error.

At certain times it was customary for a king to take his son, or other heir, as a coadjutor, and the two monarchs ruled together for a time. Unless we know the exact length of time during which this combined rule lasted, we shall again have a source of error, for each king has been credited with the full number of years during which he reigned, whether alone or in conjunction with another. In many cases we are uncertain as to the length of these combined reigns, so here we have another source of inaccuracy.

Neither of the above are very serious, and were it only for them we could calculate the date of Menes by adding up the lengths of the reigns of all the kings, and by this means of dead reckoning come to a conclusion which would be correct to within a very few hundred years. There is, however, a third and much more serious source of error. Twice during the Dynastic period the regular rule of the Egyptian monarchs was disturbed for a time, in both cases by barbarian invaders. One of these occasions was between the Sixth and the Eleventh Dynasties, the other between the Twelfth and the Eighteenth. These are known as the first and second Intermediate periods. During these times, or during part of them at any rate, foreign and barbaric kings were governing all or part of the country, while during some part, though for how long is uncertain, native dynasties were ruling some part of the country, or were claiming to do so. During these unsettled times the country was in disorder and few monuments were erected, so that we have scarcely any inscriptions with which to check the traditional accounts; moreover, the lists of kings give round numbers of years for these periods and are clearly not to be depended upon as an accurate account of the passage of time.

For a long time there was considerable uncertainty as to all dates prior to the rise of the Eighteenth Dynasty, and Egyptologists sought for some means to arrive with certainty at the earlier dates. At last an astronomical means was found, which enabled the dates of the Twelfth Dynasty to be fixed with a small margin of error, but this astronomical evidence has been differently interpreted by experts. A similar piece of evidence, though not so precise, gave some indication of the dates of the early dynasties. To understand this evidence we must consider the Egyptian calendar.

At a very early date, far back in predynastic times, the Egyptians seem to have had a year consisting of twelve months, each of thirty days, making, of course, 360 days in all. Then, some time before 4000 B.C. it is believed, they discovered that this was not the accurate length of the solar year, and they added five additional days. They did not realize, however, until long afterwards, that the length of the solar year is approximately 365¼ days, nor, after they had discovered their error, did they amend their calendar and add an extra day in leap year to make good the deficiency until the Julian calendar was forced on them by Julius Cæsar in the first century before the Christian era.

It is clear from the above statement that four years after Midsummer Day had been fixed in the calendar it would have occurred one day before the day that was actually the longest, and that every four years it would recede one day back and further from the true Midsummer Day. In the course of 1,460 years—that is to say, 365 × 4—it would have come back to its original place, and the Midsummer Day in the calendar would have coincided with the real Midsummer Day.

This was recognized at a later date, when this period of 1,460 years was called a Sothic cycle, from Sothis, the Egyptian name for the star we know as Sirius, which arose in the morning near the sun a few days before Midsummer Day, and so warned the priests, who were on the lookout, that the true Midsummer Day was approaching. In works written during the last centuries before the Christian era there are several references, which enable us to fix the last occasion on which the two midsummers, the real one and that in the calendar, coincided, and by adding multiples of 1,460 to this date we can fix the earlier occasions on which this coincidence took place. The first occurrence of this coincidence is believed to have happened in 4241 B.C.

Some years ago there was found in Egypt a papyrus of the Twelfth Dynasty, known from the place of its discovery as the Kahun papyrus. This, which is now in Berlin, mentioned that in a particular year the longest day occurred on a certain day of a certain month. It was, therefore, possible to place this date in its true place in the Sothic cycle and, since the lengths of the reigns of the Twelfth Dynasty kings were well known, to calculate the date of the beginning of the dynasty. This was fixed by Dr. Edouard Meyer, of Berlin, at about 2000 B.C., and most other authorities agreed with him. There was, however, one very distinguished dissentient, Sir Flinders Petrie. By accepting this date and working out the dates of the kings in relation to it, it was found that the second intermediate period when Egypt was governed by the Shepherd Kings, was far shorter than had been stated by the early historians. Sir Flinders, therefore, added another cycle, and suggested 3460 as the date of the beginning of the Twelfth Dynasty, though this made the period of the Shepherd Kings far longer than tradition had stated.

There still remained the dynasties preceding the first intermediate period, dynasties that are known collectively as the Old Kingdom. Meyer found some references, not quite so clear as the Kahun papyrus, and made a close study of a list of kings on the fragment of a monument now at Palermo, and known as the Palermo stone, and from these he arrived at the date 3315 B.C. as the approximate date for the unification of Egypt by Menes. Professor Breasted, of Chicago, feeling that the date suggested by Meyer was rather more precise than the evidence at his disposal warranted, put forward 3400 B.C. as an approximate date, while a few years ago Dr. H. R. Hall, believing that the very short time allotted to the intermediate periods was insufficient to allow of the changes which he found occurring in the pottery, suggested that the date should be 3500 B.C. Lastly, in 1925 Dr. Meyer amended his date to 3197 B.C. Sir Flinders Petrie, who keeps these dates one Sothic cycle before those suggested by the others, claims that this date should be 5500 B.C., while Dr. Borchardt, of Berlin, has recently suggested 4186 B.C., though it is said that this date has not been accepted by any of his compatriots.

The vast majority of Egyptologists and other archæologists accept one or other of the smaller dates, and there is not much more than 300 years between the earliest and the latest of these. The Cambridge Ancient History has accepted that of Dr. Hall, while Sir Arthur Evans, who first utilized that of Breasted, has more recently in his great work on Crete adopted the date first suggested by Meyer, and has given reasons, from the evidence he found in the Palace of Knossos, why the date put forward for the Twelfth Dynasty by Sir Flinders Perie is untenable. A few years ago Dr. H. Schaefer found at Luxor a number of fragments of pots, on which inscriptions had been written in ink. These he gave to the museum at Berlin, where the inscriptions were read and translated by Dr. Kurt Sethe, who published them in 1926, pointing out that they dated from the latter part of the Eleventh Dynasty, and that they contained curses upon the Asiatic tribes and princes that had attacked Egypt during the first Intermediate period. In 1927 M. René Dussaud pointed out that many of the proper names used in these curses were such as were employed in documents written under the First Dynasty of Babylon, which, as we have seen, arose rather before 2000 B.C. This seems to support the shorter as against the longer chronology.

It seems almost certain that the dynastic period began some time between 3500 and 3190 B.C., and, in the opinion of the author, between 3400 and 3200 B.C., but when we come to predynastic times we have nothing to guide us, except that a revised calendar, with the five extra days, leading to an approximately accurate method of ascertaining Midsummer Day, was established in 4241 B.C. Since the need of such an accurate calendar would not have been felt until the people had taken to an agricultural career, and needed to know when to sow their corn, we must suppose that grain growing had been practised in Egypt for some time prior to that date. The only estimate that has been made of the length of the predynastic period is that put forward by Sir Flinders Petrie; this is in keeping with, and in proportion to, his greatly extended dating of the dynastic period, and cannot well be accepted except by those who agree with his system of chronology as a whole.

Here we must for a moment leave the consideration of the chronology of Egypt and turn to that of Mesopotamia. For this region the evidence that we possess is very similar to that existing for Egypt. We have fragments, quoted from Berosus, in the works of Josephus and Eusebius, which give us a list of dynasties with the lengths of each, though we have not so full a list of kings. This deficiency is, however, made good to some extent by certain Babylonian and Assyrian annals and by the early lists of kings to which reference has already been made. There are also, for certain periods, so many inscriptions that the exact sequence of the kings and the lengths of their reigns are known. But for one defect we should be able to arrive at quite early dates by the method of dead reckoning, with only a small margin of error. We lack, however, complete information respecting the Kassite kings, a dynasty of foreign invaders, who were the third to rule at Babylon. We should, therefore, be in considerable doubt as to the dates of the First Babylonian Dynasty, were it not for an important piece of astronomical evidence.

Some years ago there was found an astrological tablet, giving certain observations as to the behaviour of the planet Venus in the eighth year of Ammizaduga, the tenth king of the First Babylonian Dynasty. Various computations have been made by Dutch, German, and English astronomers, and at last it seems agreed that in the computation of Dr. Fotheringham we have the correct solution and that the eighth year of this king's reign fell in 1921 B.C. Since the exact lengths of the reigns of all the preceding kings of this dynasty are known, it is easy to determine that the accession of Sumu-abu, the first king of that dynasty, was in 2169 B C. The lists of the kings, to which reference has been made in a former chapter, and which begin with the eleven antediluvian monarchs, end with the dynasty that ruled at Isin, the last Sumerian city to retain its independence. This city was captured in the nineteenth year of Sin-muballit, the fifth king of the First Babylonian Dynasty, and we can calculate from the dates already ascertained that the dynasty of Isin came to an end in 2069 B.C. Thus we can date, with fair precision, probably with absolute correctness, the last year of the last king of the last dynasty mentioned in those early lists of kings.

As we have seen in a former chapter, we have, with very few exceptions, a complete list of the kings that reigned in Mesopotamia from the flood to the fall of the dynasty of Isin, as well as of eleven antediluvian monarchs. We have also, again with a few exceptions, the lengths of the reigns of each king, and these are of reasonable length as far back as the First Dynasty of Ur, the third after the flood. Lastly, we have for several years known of an inscription set up by the son of the first king of this dynasty, and quite recently Mr. Woolley has found a lapis-lazuli seal, inscribed with the name of the first monarch's wife. It would seem that it would be an easy matter to determine, by dead reckoning, the date of the rise of the First Dynasty of Ur.

We have seen, however, in the case of Egypt, that there are dangers in accepting implicitly the results of dead reckoning, and it has been argued with much force that many of these dynasties may have ruled contemporaneously. To a certain extent this seems fairly certain from some expressions contained in the lists themselves, but to what extent this overlapping occurred is a matter of dispute. In 1923 Professor Langdon suggested that Mes-anni-padda, the first king of Ur, began to reign about 4216 B.C.; a few years later he reduced this date to about 4000 B.C., but in the preface of this work he further suggested, as the result of Fotheringham's latest calculation as to the eighth year of Ammi-zaduga, that this date should be reduced by 56 years, bringing it to 3944 B.C.

Dr. H. R. Hall believes that this date is far too early, and he has adopted a much later one, based on arguments which can only be briefly summarized here. Many years ago some French explorers excavated the mound of Telloh, the site of the ancient city of Lagash, and discovered there a great quantity of inscriptions, describing the actions of a number of kings and magistrates who ruled there in early times. The latest of these, it could be shown, were contemporary with the kings of the Third Dynasty of Ur, which immediately preceded the Dynasty of Isin, already referred to, while the earliest was a very distinguished personage known as Ur-Nina. Since the dates of the Third Dynasty of Ur are known with almost exact precision, and the documents from Telloh form an almost complete series, it has been possible to calculate the dates of the kings and magistrates of Lagash with very fair accuracy. By this means it has been estimated that Ur-Nina lived about 3100 B.C. Dr. Hall considers that the style of the art and the writing belonging to the First Dynasty of Ur so nearly resembles that found at Lagash in the time of Ur-Nina that the two must be approximately contemporary, though the First Dynasty of Ur is probably slightly the earlier of the two. He has, therefore, suggested that the date of the First Dynasty of Ur was about 3,200 B.C., and this date has been adopted by Mr. Woolley, who is excavating that site; Hall, however, admits that it might have begun somewhat earlier and that Mes-anni-padda might have ascended the throne of Ur as early as 3300 B.C.

There is thus a discrepancy of about 650 years between the earliest date suggested by Hall and the latest put forward by Langdon, and it is not possible as yet to arrive at the date of Mes-anni-padda with precision. The present writer believes that the true date will be found to lie between the two already suggested, and, in all probability, nearer to that proposed by Langdon than to that suggested by Hall. Before the First Dynasty of Ur came the First Dynasty of Erech, with about eight kings, and before that again the First Dynasty of Kish with about twenty-one. These twenty-nine kings must, at the lowest estimate, have reigned for about 700 years. If, therefore, Mes-anni-padda ascended the throne of Ur about 3800 or 3700 B.C., which the present writer believes to be more likely dates than those suggested by the others, the

First Dynasty of Kish, which began when the great floods had ceased, must have begun about 4500 or 4400 B.C. Allowing, as a rough guess, that the floods lasted for about 200 years and that the eleven antediluvian monarchs took up between them about 300 years, we are brought back to the date 5000 or 4900 B.C. as the date when village settlements or cities with head-men or kings were first recorded as having settled in the Mesopotamian plain.

Now we have already seen that some, at any rate, of the inhabitants of these antediluvian cities, especially those of Eridu, cultivated grain of some kind, and the very existence of organized villages suggests that in all of them agriculture was practised. We have seen reason for believing that grain was first cultivated either in Syria or farther north in the valley of the Euphrates; the art of agriculture must, therefore, have been carried into Mesopotamia from elsewhere. We must, therefore, place the discovery of this most important art, which has worked such a great revolution in the life of mankind, at a date somewhat prior to 5000 B.C., though how much earlier it is at present impossible to conjecture.

Thus far we have been arguing back from the known to the unknown, from well-ascertained dates, by a process of dead reckoning, checked occasionally by astronomical evidence, to those that grow more and more uncertain as we recede into the dim past, until in Egypt we have no dates to guide us before the accession of Menes, placed according to the shorter chronologies somewhere between 3500 and 3200 B.C., while in Mesopotamia before 3100 B.C. there is a discrepancy of 700 to 800 years between the various dates proposed. It may be well to note, however, that Mr. Woolley, who places the accession of Mes-anni-padda at the latest date—namely, 3200 B.C.—has found recently some marvellous remains twelve feet below the foundations of buildings dating from the First

Dynasty of Ur. These he has dated provisionally at about 3500 B.C. Among these remains are remarkable examples of the goldsmith's art, beautiful work in lapis-lazuli, an elaborately decorated harp, a limestone slab on which is carved in relief a representation of a chariot with solid wheels, as well as brick vaults showing not only corbelling, but true arches. These, at the very late dating adopted by Woolley, are of the same period that Hall would place Menes, the first king of the First Egyptian Dynasty, and precede that traditional hero by a century or more, according to the chronologies adopted by most other Egyptologists.

During their first two dynasties the civilization of Egypt was on a much lower standard, their jewellery was crude, and their buildings simple and of sun-dried brick. Only in the reign of Khasekhemui, the last king of the Second Dynasty, do we find jewellery at all comparable, inferior though it is, with that found in these early tombs at Ur, and in his tomb we find the first stone building, a plain chamber of hewn limestone blocks. It is not until the time of Zoser, his son and successor, the first king of the Third Dynasty, who succeeded his father about 3000 B.C., that we find any signs of elaborate architecture. Under this monarch, and under the inspiration of Im-hotep, his Prime Minister, physician, and architect, we find for the first time the appearance of a beautiful style of architecture in that grand temple before his stepped pyramid at Sakkara recently brought to light by Mr. Firth. Until the time of Zoser and his Minister Im-hotep, afterwards looked upon by the Egyptians as the father of science, civilization was in a low state and very inferior to that found in the early tombs at Ur, which even Woolley places 500 years earlier.

There is another way of approaching these early dates, though it is far from precise; this is the geological method. It may, however, help us to check the early figures that we have obtained so far by the means we have hitherto employed. It may also, perhaps, help us somewhat in arriving at comparative dates for Egypt and Mesopotamia in very early times.

Everyone to-day has heard of the Glacial Period, or the Great Ice Age, when a large sheet of ice covered Scandinavia and the snowfields and glaciers of Switzerland reached down many hundreds of feet below their present level. There is still a difference of opinion among scientific men as to whether there was one or several of such periods of extreme cold with genial intervals. This disagreement need not concern us here, for we shall only discuss certain conditions which existed while the last Ice Age was passing away.

It has been pointed out by Drs. Penck and Brückner, from evidence obtained in the Alpine region of Switzerland and Austria, and by Baron de Geer, from evidence gathered in Sweden, that the retreat of the glaciers in the former region, and that of the ice-sheet in the latter, were not quite steady, but that there were a few short periods in which the glaciers and the ice-sheet ceased for a time to retreat, and may even have advanced somewhat for a brief interval. Every glacier carries down with it much mud and many large boulders; these are deposited at its foot when it melts, and forms a heap or bank, known as a moraine. The ice-sheets, in the same way, form a long moraine at their outer edges. When glaciers and ice-sheets are retreating steadily, the moraines are small and form each year in a different position, so that they become a sheet of mud and boulders rather than a bank. When, however, the ice-sheets and glaciers remain for many years without shrinking, the moraines become piled up into high banks, and this is also true if they advance to some extent.

Penck and Brückner noticed in the Alpine region evidence of three such pauses or re-advances of the glaciers, and they gave to these periods the names of Bühl, Gschnitz, and Daun. Many years later they found by some of the Swiss lakes three successive moraines, which seemed to belong to the Bühl phase, and they suggested that this phase was threefold, and that the glaciers had halted or re-advanced three times at very short intervals. In Sweden, Baron de Geer noted a great moraine, crossing the Swedish lakes, which was known as the Fenno-scandian Moraine, and which exhibited also a threefold structure, and evidence of a later pause in the retreat of the ice-sheet near Lake Ragunda; this last episode he called the Ragunda Pause. There is every reason for believing that the Bühl and the Fenno-scandian moraines represent the same re-advance of the ice, due to a slight increase in the severity of the climate, while the Ragunda Pause took place when the Gschnitz moraines were forming in the Alps during another cold period.

Now, as the ice-sheet retreated over Sweden it left behind each year a thin layer of mud, which dried hard in the summer-time, while a fresh layer was laid upon it the following winter. Baron de Geer has found several such sets of layers, or *varves* as he calls them, and with the aid of his pupils he has counted these, and has reached the conclusion that the Ragunda Pause took place about 4500 B.C. As we have seen, it seems likely that the Gschnitz moraines in the Alps were laid down at the same time, and that during this period there was a phase of increased cold.

It has been noticed by Swedish geologists that at the time of the Ragunda Pause there was a slight raising of the land or a lowering of the sea. This has led some to believe that all the ice ages, including such minor episodes as the Bühl, Gschnitz, and Dawn phases, were due to an elevation of the land. This view has not yet been generally accepted, but is gaining ground among scientific men; in any case, we have positive evidence that the land stood higher in Scandinavia about 4500 B.C., and there is much reason for believing that the same conditions prevailed all over Europe and over parts, at any rate, of Asia and Africa.

If this be true, we can gain from this information some help towards the early dating of civilization. If the Armenian mountains were raised many feet above their present height, the snowfields, which at present cover their highest reaches, would have been considerably increased, and the spring floods, due to the melting snow, would have been more extensive and would have lasted longer. As it is, the flood waters of the Tigris and the Euphrates descend into the Mesopotamian plain at different times, and one has subsided before the other begins. Were both to have an increased intensity and a longer duration, the flood water would cover most of the land below Bagdad during the whole of the late spring and early summer and make the cultivation of the plain impossible. It is tempting, therefore, to think that the episode, known in Mesopotamia as the Flood, was due to that elevation of the land which caused the formation of Gschnitz moraines in the Alps, and which made the Scandinavian ice-sheet pause in its retreat at Lake Ragunda.

In very early days the Delta of the Nile seems to have been one large swamp; at least, that is the opinion of Professor Newberry. It is easy to realize, however, that the raising of the land, even by twenty or thirty feet above the level of the sea, would cause this swamp to become drained and to expose a large area of exceedingly rich land. Such an expanse would tempt grain-growers, especially those cultivating crops in the relatively dry soil of Palestine, to move into this fertile area, and it is possible—nay, even probable—that it was this temptation that brought into Egypt those newcomers, who carried with them the wavy-handled pots and the pear-shaped mace-heads that in sequence date 40 usher in the Middle Predynastic period. That these newcomers brought in the art of cultivating wheat, or, more accurately, Emmer, seems certain, though whether they introduced also the cultivation of barley depends, as we have seen, upon the exact dates of the graves near Silsileh and at Naga-ed-Dêr.

Thus this fresh evidence and the arguments derived from it seem to confirm our former conjecture that the Flood occurred during the centuries around 4500 B.C., that grain was grown in Mesopotamia before that date, though it was at this time that wheat was first brought into Egypt, where, it is just possible, but by no means certain, barley had been previously cultivated as the result of an independent experiment.

CHAPTER VI

HOW DID AGRICULTURE BEGIN?

Our third question is the most difficult to answer, for, from the nature of the case, it is only possible to make a more or less intelligent guess at the solution. We have seen that man in a hunting state was purely carnivorous and ate nothing but meat, and experience of primitive peoples has demonstrated that such folk are very conservative in their habits, and only with great difficulty are they persuaded to change them. Some great force must have been necessary to compel man to abandon his free hunting life with its meat diet and to take, even though in part only, to a vegetarian fare. The only force strong enough to encompass his fall from the hunting state must have been hunger, which can have been produced only by the growing scarcity of the beasts of the chase.

We have already seen that, as time went on, the women were compelled to absent themselves from the hunting pack for longer and longer intervals as the demands of their infants increased, and we have suggested that during these periods, when food from the male group was delayed owing to lack of success in the chase, the women may have supplemented their fare with nuts and berries and perhaps with edible roots. It seems almost certain that it was the women who first introduced these new vegetarian elements into the primitive bill of fare, and we can imagine how one such woman, finding her man desperately hungry after many days of unsuccessful hunting, persuaded him, much against his will, to taste of her supplies. The woman tempted him, and he ate of this unusual, and to him forbidden, fruit, and henceforth he was compelled to earn his food by the sweat of his brow.

That this is not altogether an imaginary picture may be learned from the habits of simple peoples still living. Some thirty years ago Mr. Walter Roth travelled among the natives in North-West-Central Queensland, studying their habits. In the Boulia district he found that these people, still in the hunting stage, collected the seeds of several grasses to supplement their food supply, while other seeds were collected and eaten by the Mitakoodi of the Cloncurry district, and by the Kalkadoon in the Leichhardt-Selwyn district. In 1912 Professor and Mrs. Seligman were travelling in the Upper Nile basin and visited the village of Faragab in Kordofan. Here they came across the Gawania, a very dark tribe, who usually grew sufficient grain to supply their needs. Owing to a shortage of rain during the previous winter all their crops had failed, and in desperation they had been compelled to collect and eat the very unpleasant and far from nutritious seeds of the wild grass known there as *heskenit*. These are only two instances of many that could be cited, one of a hunting tribe and the other of a primitive agricultural people, reduced by the failure of their crops to have recourse to wild grass seeds.

It is not difficult, therefore, to realize how man, or, more correctly, woman, first took to eating wild grain. It is less easy to explain how she learned to cultivate it. Grant Allen once suggested that grains from wild plants used for food were scattered as offerings over the grave of a departed friend. These sprouted and grew luxuriantly in the freshly turned soil, and this gave to mankind their first idea of cultivation. By degrees the upturned soil grew to greater dimensions than were necessary for the grave, until it became a field with a grave at the corner. For long after, so he suggested, it was customary to bury someone each year at seed-time in one corner of the cultivated fields, even if a victim had to be sacrificed for the purpose, until, as the people grew more civilized, an animal was substituted for the human victim.

Another though more prosaic origin is possible. We can imagine a hungry woman collecting with great labour a quantity of wild grass seeds and storing them in a basket, gourd, or leather bag. In this, after a long search to enable her to collect sufficient for her needs, she would bring the results of her labours back to her home. One day an accident happened and the store of grain became spilled and scattered on the bare hill-side, or perhaps her husband, disapproving of the novel vegetarian fare collected by his wife, reproached her for her innovation, and threw down on the bare ground the store that she had collected with so much pains. We can imagine the poor woman's grief and disappointment at this loss; also her joy when, after many months, she found a rich crop of the desired grasses springing up at her door. We can well imagine that she repeated the process, which saved her from a laborious journey in search of food, and she would notice that the plants grew best where there were no weeds to interfere with their growth. It was a short step from this to take a stone hoe, such as had been used for the purpose of digging up edible roots, and to remove the weeds, thus turning over the soil and enabling the grain to germinate better and to grow a heavier crop. When this had been achieved, the first steps in agriculture had already been made.

Let us now see how these ideas will fit into the historical and geographical framework that we have outlined in earlier chapters. During the last great Ice Age, known as the Würm, the climatic conditions now obtaining within the Arctic Circle descended in Europe to about latitude 53°, and somewhat similar conditions prevailed on the North American continent.

Outside the Arctic Circle is a zone, in which cold, dry, tundra conditions prevail, such as we find to-day in the northern parts of Siberia. Outside this, again, is a zone of storms, then another of light rainfall, another of still lighter rainfall shading off to an almost rainless zone, such as we find now in the Sahara Desert. During the time of the Würm Ice Age, owing to the great increase in the Arctic area, all these zones lay much farther south than they do at the present day, and what is now the Sahara Desert must have been grassland, with woodlands in the regions with the greatest rainfall.

As the ice-sheet began to diminish in size, the plain of North Europe would have become a cold, dry steppe, full of hoofed animals feeding on the rich herbage in the summer-time. Here man, during the cave period, would have found bison, wild oxen, wild horses, and reindeer in profusion, and, during the summer months at any rate, his larder would never have been empty. As the ice still further retreated, the tundra zone contracted, and the storm zone crossed the European plain. The rainfall on the Sahara became lighter, and dry steppe conditions prevailed in that region. First a pine forest invaded Europe, coming from the south-east across Asia Minor, and the steppe animals retreated to South Russia and Turkestan, which have always been free from trees, while the reindeer was replaced by the red deer. This began about 9000 B.C. About two thousand years later the rainfall on the European plain increased, and the pines were replaced by deciduous trees, mainly oaks with a thick undergrowth. The hunting communities were separated from one another by dense woodland, their game had disappeared, and there was nothing to be done but to settle down by the seashore or by the banks of lakes and rivers, and to pick up such small game as had survived.

About the same time the light rainfall on the Sahara came to an end, the dry steppe gave place to desert, the wild beasts fled to the south, and there seems to have been a general exodus of the human inhabitants, who, armed with small flint weapons, dispersed in almost every direction. These two events, approximately contemporaneous, brought what is known as the Cave period or the Upper Palæolithic period to a close at a date, which, following the evidence supplied by de Geer, we may fix provisionally between 7000 and 6000 B.C.

During the Epipalæolithic period that followed, the miserable descendants of the Upper Palæolithic hunters, hemmed in by the ever advancing oak forest, killed out such small game as had survived, and from living on meat took to sustaining themselves on shellfish, eking out this meagre fare with nuts and berries in their season and a few edible roots. The hunters from the Sahara kept to the few open spaces left, the bare limestone hills and patches of sandy country.

Epipalæolithic man must often have gone very hungry, and he was reduced to eating anything that he could find, however unpalatable or uninviting. Like the aboriginal tribes in Queensland or some of the people of Kordofan he must sometimes have collected for food the seeds of grasses in those regions in which suitable grasses were to be found. He may even have tended and cleared round plants that produced these edible seeds. At length he, or more probably his wife, discovered that if some of these seeds were sown on a cleared patch of soil a better crop was the result. Thus it would be unnecessary to wander so far afield to fill the baskets and to provide an adequate meal. In some such way, we may well imagine, arose the cultivation of grain, which enabled men to leave behind them the savage state of the hunter, thus setting their feet on the lowest rung of the ladder of civilization.

We may thus picture the inhabitants of Syria, or the dwellers in the foot-hills near the banks of the

Euphrates, having nearly killed out the game upon which they had formerly subsisted, searching for nuts, berries, and roots, like the Epipalæolithic inhabitants of Europe, and, being unable, like their western contemporaries, to live on clams and limpets, with an occasional oyster feast. Hungry and despondent they were at times driven, like the inhabitants of Queensland or Kordofan, to collect the seeds of wild grasses, until there arose a woman, who was to be their saviour and to lay the foundations of civilization.

It was, we may well believe, about 5000 B.C., or conceivably some centuries earlier, on the slopes of Mount Nysa, in Phœnicia, far away, that this woman collected the seeds of barley and of Emmer, which there grew wild, and scattered them upon a bare surface of the mountain side, where they were watered by the dew of Hermon that descended upon the mountains of Zion, so that the seed that she had cast upon the hillside she found increased a hundredfold after many days. This woman, one likes to think, was immortalized by the Egyptians as Isis, and as Cybele, Agdistis, and Dindymene by the peoples of Asia Minor; later by the Greeks as Demeter and by the Romans as Ceres. Her memory has been preserved almost to our own time by our country folk as the Corn Goddess, whose effigy was carried to the barn in the last harvest waggon.

BIBLIOGRAPHY

Breasted, J. H.: *A History of Egypt.* (New York. 1912.)

Cambridge Ancient History. Vol. I. (Cambridge. The University Press, 1923.)

Delaporte, L.: *Mesopotamia: the Babylonian and Assyrian Civilizations.* (London. Kegan Paul, 1925.)

Elliot Smith, G.: *The Ancient Egyptians and their Influence upon the Civilization of Europe.* (London. Harper, 1911.)

Frankfort, H.: *Studies in Early Pottery in the Near East.* (London. Royal Anthropological Institute, 1924 and 1927.)

Myres, J. L.: *The Dawn of History.* (Home University Library, London. Williams and Norgate.)

Oxford Edition of Cuneiform Texts. Vol. II. (Oxford. The Clarendon Press, 1923.)

Peake, Harold: *The English Village.* (London. Benn, 1922.)

Peake, H., and Fleure, H. J.: *The Corridors of Time.* Vols. II., III., and IV. (Oxford. The Clarendon Press, 1927.)

Percival, J.: *The Wheat Plant (a monograph).* (London, 1921.)

Pumpelly, R.: *Explorations in Turkestan.* (Washington. The Carnegie Institute, 1908.)

Stapf, O.: *The History of Wheat.* (Suppl. to Journ. Bd. Agric. London, 1910.)

Vavilov, Professor N. I.: *Studies on the Origin of Cultivated Plants.* (Bull. Appl. Botany and Plant-Breeding, Vol. XVI. Leningrad, 1926.)

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THE WEATHER

AN INTRODUCTION TO CLIMATOLOGY

By C. E. P. BROOKS, D.Sc.

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THE WEATHER

CHAPTER I

THE SUN AND THE ATMOSPHERE

THE word "climate" comes from a Greek word meaning "to incline," in the sense of the inclination of the sun's noonday rays to the vertical. The word was happily chosen, for climate is generalised weather, and weather, like life, is a gift of the sun; and as the elevation of the sun declines from the equator towards the poles, so, generally speaking, do the intensity of climatic phenomena and the luxuriance of life. If there were no sun there would be no differences of temperature, no storms, no wind, no rain, no weather. But equally there would be very little climate and weather if the earth were flat, for it is the spherical shape of the earth which gives to different latitudes different inclinations of the sun's rays at noon—that is, different climates. Hence we have to consider two different aspects of solar radiation—the quantity of heat which the earth as a whole receives from the sun, and the way in which that heat supply is distributed in different latitudes. Logically the former of these aspects should be considered first, but the relative distribution of the sun's heat over the earth was known long before its absolute value had been determined, and the relative distribution has played by far the greater part in the development of *meteorology*, which is the scientific study of weather. We are therefore historically correct in taking the relative distribution first.

Any flat surface exposed to the sun receives most heat when it is turned at right angles to the sun's rays. Thus in England the south side of a hill receives more heat from the sun than does a plain, and a plain more than the north side of a hill, because the south side is turned towards the sun and the north side is turned away from the sun. Compared with the tropics, we may regard all the rest of the northern hemisphere as the north side of a hill, turned away from the sun, and growing steeper and steeper towards the pole. Hence, even outside the atmosphere, the polar regions receive less heat than England, and England less than the tropics, the proportions being: pole, 10; latitude, 52°, 16; equator, 24. The latitude of London receives more than one and one-half times as much radiation as the poles, but only two-thirds as much as the equator. Each line of latitude, however, receives the same amount along its entire course, and the same latitudes in the northern and southern hemispheres receive the same amount of heat during a year. This distribution of solar radiation is the "solar climate," which is the original meaning of the word climate.

The spheroidal shape of the earth comes into the problem in another way. Calculations show that at midsummer the pole, because of its twenty-four-hour day, actually receives at the top of the atmosphere more heat from the sun than does the equator, but everyone knows (by hearsay) that the equator is the hotter. There are many reasons for this, but one of the most important is that in very high latitudes the sun never rises high in the heavens, and to reach the surface at the poles the sun's rays have to penetrate through a very great thickness of air. Even at midsummer their path through the air at the pole is more than twice as long as that at noon on the equator. Everywhere on the earth's surface, as the evening sun drops towards the horizon, its rays become enfeebled; the polar day is, so to speak, one long evening, and even the twenty-four-hour day cannot make up for this additional handicap imposed on the poles.

Thus the first fact of climate is that the temperature of the earth's surface and of the air near the surface decreases from the equator to the poles. The early Greek meteorologists thought that the equator must be too hot for human life and the polar regions too cold, and if each part of the earth's surface were independent of the other parts they would have been right. But air is a fluid, and, as will be shown in the next chapter, you cannot warm one part of a layer of air and leave the other parts cold without setting the air in motion. The atmosphere has often been compared with an engine because of this property; an engine consists of a working substance, such as air or steam, a boiler where heat is supplied to the working substance, and a condenser where this heat is taken away again. The working substance travels from the boiler to the condenser, and on the way it sets the machinery going, but in the engine of the atmosphere the working substance and the machinery are the same. There are several useful illustrations here:

1. The efficiency of the engine depends on the difference of temperature between boiler and condenser. You cannot set an engine going by warming it gently all over. So the winds depend on the differences of temperature between the different parts of the earth, and not on the average temperature of the earth as a whole.

2. The working of the engine reduces the heat in the boiler and warms the condenser; so the atmospheric engine reduces the heat near the equator and warms the poles.

3. There are several sorts of engines—air engines, steam engines, etc. The working substance of the atmospheric engine is a mixture of air and steam, or water vapour, for water is evaporated in low latitudes, and some of this vapour travels to higher latitudes before it is condensed as rain or snow.

We are thinking of these three processes when we say that the sun's heat, and its unequal distribution over the earth's surface, cause the winds and the weather.

All this was known long before meteorologists had made much more than a guess at the actual amount of heat sent to us by the sun, for this amount is not easy to measure. Our instruments tell us readily enough the heat of the sun's rays where they strike the earth's surface, but this is not quite the same thing. Part of the sun's radiation is absorbed during its passage through the air, and part is broken up and scattered by the molecules of the air, just as the light from a street lamp is partly absorbed, partly broken up and scattered by the water droplets of a fog. On a high mountain the sun is " hotter " than on a low plain, because it has passed through a smaller thickness of air to reach the mountain; for the same reason the sun is " hotter " at noon than in the evening. The quantity which we want to measure is the heat which would fall on a mountain high enough to penetrate right through the air into space; but there is no such mountain, and if there were we could not take observations there. Even Mount Everest only penetrates through about four-fifths of the air.

The way in which the problem was attacked is briefly as follows: First, the observers went to a dry region near the tropics; dry because dry air cuts off much less of the sun's heat than does moist air, and also because there is less chance of cloud, and near the tropics because there the sun is almost overhead and has to penetrate a smaller thickness of air than nearer the poles. Next, they selected a mountain which, while not too high to make access to the summit impracticable, yet penetrates through a good part of the atmosphere. The first chosen was Mount Wilson, Arizona; later a still more suitable site was found in the Andes of Peru. The instruments being set up, observations were begun on the first cloudless day, and were taken several times at short intervals during the latter part of the morning. Suppose the station is on the equator and the date is the spring equinox, March 21. At noon, when the sun is directly overhead, its rays pass through exactly the thickness of the atmosphere, which we will call an air mass of one, and this thickness of air absorbs a proportion of its radiation—say, one quarter—and only three-quarters reach the ground. At 8 a.m. the sun is shining obliquely, and the path of its rays through the air is twice as long as at noon. By the time the sun's rays have penetrated halfway through the atmosphere their intensity has been diminished by one quarter. In traversing the remaining half of the air they are again diminished by one quarter, not of their original value, but of the new value of three-quarters, so that when they reach the surface their strength is only nine-sixteenths of that outside the atmosphere. The diminution by one quarter for one thickness of the atmosphere was only a guess, but theoretically the true value can be calculated from only two measurements at different elevations of the sun. In practice there are difficulties (there always are!); observations are not taken so early as 8 a.m., and various corrections are necessary, but the principle is the same.

The first satisfactory observations were made by Dr. C. G. Abbot on Mount Wilson in the summer of 1905, and all the measurements since that date give a mean value for the solar radiation of very nearly two (1·935) gram calories per square centimetre per minute. This means that if a gram of water in a vessel one centimetre square could be raised to the top of the atmosphere and exposed to an overhead sun, and also prevented from giving out any heat, its temperature would rise by two centigrade degrees each minute. If an inch depth of ice-cold water were put into a saucepan and exposed under the same conditions, it would boil in just over two hours. This quantity of nearly two gram calories per square centimetre per minute is termed the " solar constant." It is not really constant, since it varies according to the number of spots on the sun and from other causes; but the variations probably do not exceed five per cent on either side of the average value.

One of the most fascinating branches of meteorology is the study of the life history of a sunbeam. Since the earth is not getting hotter, the solar heat is not accumulating, but is being given out again by the earth as fast as it is received. It is necessary here to say something about the nature of radiant heat. Everyone nowadays has heard of " wireless " waves in the ether, and knows that they are of different " lengths," from several thousand metres down to a few metres. Radiant heat, such as that sent out by the sun or by a red fire, consists of similar waves in the ether, but of very much shorter length, so that while wireless waves are measured in metres, heat waves are measured in ten thousand millionths of a metre. Like wireless waves, heat waves are of different lengths; the hotter the radiating body, the shorter the waves. Everything sends out heat waves; those from hot bodies, of relatively short wave length, are termed " short-wave radiation," and those from bodies at ordinary temperatures are termed " long-wave radiation." Again, just as wireless waves of different lengths have different powers of penetration, so have heat waves of different lengths. The short-wave radiation from the sun penetrates fairly easily through the air, but the long-wave radiation from the cooler earth does not penetrate air easily, and when the air is moist it almost completely absorbs long-wave radiation. Remember that everything is radiating some heat all the time. On a hot day we may be acutely conscious of the radiation from the sun; a passing cloud obscures the sun, and we may feel the radiation from the sun-baked ground. The air radiates heat, and the radiation from the clouds to the earth may be felt—and cursed—on a sultry summer night, while the same radiation earlier in the year may save the orchards from a spring frost. The sun sends us heat only during the daytime, but the earth and the air and the clouds are giving back heat all day and all night.

We have already seen that some of the sun's heat does not reach the earth's surface at all. Part is absorbed by the air, and although it is true that the air passes on half of this part to the earth, it sends the other half back to space. Part is scattered by the air molecules and by particles of dust, but most of this part reaches the earth's surface in the end, though by devious routes. A considerable part of the sun's radiation strikes the upper surfaces of clouds, and, surprising as it may seem, clouds are very good reflectors. The intense brightness of woolly cumulus clouds in the sun is due to the great amount of light which they reflect, and they reflect the invisible heat rays as well as the visible light rays. Some of these reflected rays reach the surface, but the greater part are returned to space and lost to the earth.

Even when it reaches the earth's surface, the troubles of the solar radiation are not over. The ground reflects varying quantities according to its nature—dark soil least, light, bare sand and shingle most. The sea also reflects, and snow or ice surfaces reflect most of all, as Alpine climbers know. The reflection from the surface is not so great as the reflection from clouds, but altogether nearly half of the sun's radiation is sent back to space without benefiting the earth at all.

Of the half or more of the sun's heat which is not absorbed by the air or reflected, part is spent in evaporating water, especially from the sea, while the remainder goes to warm the earth's surface, but very nearly all of it ultimately goes to warm the air. The evaporation of water absorbs a large quantity of heat—it takes only one-fifth as long to raise a kettle of ice-cold water to boiling point as it does to evaporate the water after it is boiling—and all this heat is given back to the air when the water vapour is condensed as cloud or rain. The surfaces heated by the sun's rays give back their heat partly by warming the air which comes in contact with them, but mainly by radiating heat. This terrestrial radiation is " long-wave radiation," which differs from the short-wave solar radiation in having a much smaller power of penetrating air, especially moist air. Even including reflection from clouds and scattering by air molecules, the sun's rays lose on the average less than half their intensity on their way to the earth's surface, while the loss which they sustain from absorption alone is negligible—less than one-tenth. On the other hand, the air absorbs about four-fifths of the radiation from the earth's surface, and allows only one-fifth to pass straight out into space. Moist air is, in fact, almost *opaque* for terrestrial radiation.

This property of the air is of very great importance for the life of the world. For if the air were transparent to the earth's radiation, the latter would pass out to space and be lost. Being opaque, the air absorbs it and is warmed, and has itself to radiate out the heat so gained. More than half of this radiation from the air comes back to the earth again, and so warms the surface twice over. The surface of the earth in this way becomes much warmer than it would otherwise be. It has been calculated that if the air were perfectly transparent to both solar and terrestrial radiation, and if there were no clouds, the average temperature over the entire surface would be 52°.* Actually the average temperature is 59°, or seven degrees higher than the theoretical temperature, and this difference is almost entirely due to the water vapour in the air.

It is well known that the amount of water vapour in the air is very different in different parts of the earth, and also differs in the same place from time to time. This makes corresponding differences in the fall of temperature at night. In the moist equatorial regions the nights are warm, because the moist air will not let the earth's heat escape. In the arid desert, although the temperature may rise much higher during the day, the nights are cold, sometimes nearly freezing, because there is not enough water vapour in the air to absorb and return to the surface sufficient of the earth's radiation to maintain the temperature. The extraordinary winter cold of Siberia is due in large measure to the extreme dryness of the air.

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* Throughout this book temperatures are given in degrees on the Fahrenheit scale, on which freezing point is 32°.

The same property of moist air is seen in the way in which scientific farmers calculate the probability of frost at night. Suppose that in the evening the sky is clear and the temperature a few degrees above freezing point. The farmer looks at his psychrometer—an instrument for determining the humidity of the air—and compares the reading with a table of chances. If the humidity is high, he finds that the chance of frost is remote, and goes to bed with an easy mind. If, on the other hand, the humidity is low, he finds that the chance of frost is great, and he takes such precautions as circumstances direct. He may light bonfires to warm the air, but his most effective precaution is to conserve the earth's own heat by interposing between the earth and the sky some screen, such as netting or a smudge of smoke, which will intercept the earth's radiation and return most of it to the ground.

CHAPTER II

THE WAY OF THE WINDS

If one divides a basin into two halves by a vertical partition, fills one half with water, the other half with oil, and then removes the partition, the water pushes under the oil, and the oil runs over the water, until the bottom half of the basin is filled with water, and the top half with oil. Instead of water and oil, one could use cold water and hot water; the cold water being the heavier would push under the hot water, and the hot water being the lighter would run over the cold water, though in this case there would be some mixing. If one took a long trough-like basin, put a flame under the middle, and wrapped ice round each end, the water would always be getting cold at the ends and hot in the middle, and the cold water would always be pushing under the hot water, while the hot water would always be flowing over the cold water. A *circulation* would be set up, the water sinking at the ends, which we may call the poles, and flowing along the bottom of the trough towards the middle, which we may call the equator. Here it would rise to the top and flow back to the poles. Because the water over the ends of the trough is colder, and therefore weighs more than that over the middle, it presses more heavily on the bottom of the trough at the ends, and we may say that the water flows along the bottom from places where the pressure is greater to places where the pressure is less.

Substitute air for water, and we have a fair picture of what ought to happen in the atmosphere. On a small scale it does happen in land and sea breezes. During a hot afternoon the air is warmed over the land, where it rises and is replaced by cooler air flowing in from the sea, while the warmed air flows back from the land to the sea at a higher level. At night the air over the land is cooled more than that over the sea, and flows from the land to the sea as a land breeze, rising over the sea and flowing back to the land at a higher level. Similarly the air ought to flow along the surface from the poles to the equatorial regions, rise there, and flow back to the poles in the upper air. It *ought to,* but it does not. The winds in England ought to be always from north, but they are more often from west. The pressure of the air on the surface, as shown by barometer readings, ought to be greatest at the poles and decrease steadily towards the equator, but we know that the barometer generally reads lower in the north of Scotland than in the south of England. Evidently the model we have made of the circulation has left out of account some essential factor. Our model would be correct enough if the earth were as still as the ancients thought it to be, but we know now that it is not still, but spinning round on its axis like a top. The poles are still enough, but any point on the equator is rushing eastward at the rate of 26,000 miles a day, or more than a thousand miles an hour.

Suppose you are standing on the north side of a railway, and are foolish enough to throw a stone straight at a train travelling due eastwards, and hit a passenger. To the unfortunate passenger the stone would seem to come not from the north, but from the north-east, or even, if the train were an express, from the east-north-east. To anyone standing at the north pole, the earth 200 miles to the south is moving eastwards at sixty miles an hour, and if he were to blow due south, and could blow hard enough, he would cause an east-north-east wind somewhere south of him. Thus owing to the rotation of the earth about its axis, any air which started moving directly towards the equator would soon become an east wind. On the other hand, any air which started moving directly away from the equator would soon become a west wind. This seems to show that the logical outcome of the difference in temperature between the equator and the poles, combined with the earth's rotation, should be east winds everywhere on the surface of the earth, and west winds at high levels in the atmosphere. Pressure would still be highest near the poles and lowest near the equator, but we should find that instead of blowing from high pressure to low pressure, the winds steer a middle course between the high pressure and the low. In the northern hemisphere they keep the high pressure to the right and the low pressure to the left; in the southern hemisphere they keep the high pressure to the left and the low pressure to the right.

Fortunately the wind in England is not always from the east, so we have to go further still. So far we have been arguing as if the air could move about the earth as freely as a millionaire globe trotter with plenty of tact. What the air lacks is the tact; there is too much friction between the air and the things that get in its way, such as trees and mountains. It gets on better over the sea, which is why the winds are so much stronger there than over the land. Our hypothetical east winds would always be pushing at the rotating earth and trying to stop it from rotating. But if you want to push, you must have something to put your foot against, and that is just what the east winds have not. Instead of the winds pushing back the earth, the earth pushes back the winds, until finally there is just as much wind from the west as from the east. It must be so, otherwise in time the wind would stop the earth from rotating. If you are in a train, no amount of pushing the back of the carriage will slow up the train, because you are part of the moving system—that is to say, part of the train. In the same way the air is part of the earth's moving system, and no amount of pushing by the wind can slow up the earth.

The way that friction takes effect is to break up the easterly winds which come out of the polar regions into a series of whirls, like the whirls which form behind a big stone in a swift stream. These are the well-known cyclones or barometric depressions, about which there will be more to say in Chapter IV. The polar east winds curl round the centres of these whirls towards the equator, and on the equatorial side they become west winds. Since there are always several of these whirls or cyclones in existence at the same time, the result is that outside the belts of polar east winds there are other belts where the winds are generally from west. We in England live in one of these belts of westerly winds; the other belt, in the southern hemisphere, is sometimes described poetically as " the brave west winds," or more vigorously as the "roaring forties," and under its influence the old sailing clippers made some amazing passages from the Cape of Good Hope to Australia.

We must now go back to the relations between wind and pressure. We saw that our hypothetical east winds in the northern hemisphere must have high pressure on their right hand and low pressure on their left hand. That statement applies not only to east winds, but to winds from any direction. This fact was pointed out in 1857 by a Dutch meteorologist, Buys Ballot, and is set out in the following rule, termed Buys Ballot's Law: "If, in the northern hemisphere, you stand with your back to the wind, pressure is lower on your left hand than on your right." In the southern hemisphere the reverse is true; if you go to Tierra del Fuego and stand with your back to the wind, pressure will be lower on your right hand than on your left. If now in England you stand with your back to the prevailing west wind, your left hand is on the north side, and the lower pressure will be to the north. That is, pressure rises southwards, and it goes on rising throughout the belt of west winds until beyond the Azores, in latitude 30, we come to a sub-tropical, calm, anticyclonic area or region of high pressure. Beyond this anticyclone we come to more east, or rather north-east winds—the north-east trades—and pressure falls again until near the equator it is as low as over the British Isles.

You may ask, Why does not pressure go on rising right up to the equator? That is a very difficult question, to which no one has ever given an entirely satisfactory answer, but we may put it something like this. If the earth were a cylinder, and if the ends of the cylinder were still cold like the poles, and the middle still hot like the equator, the surface winds would blow direct from the ends towards the equator, and however fast the cylinder rotated it would make no difference, because all parts of the curved surface would be moving at the same rate. But the parts of the earth near the equator are very nearly cylindrical; if all the earth north of latitude 20 north and south of latitude 20 south could be cut away, the remainder would look much more like a cylinder than a sphere. Hence in this part of the world the winds blow towards the equator as they would if the earth were still, but the surface is still curved enough to deflect them to the right in the northern hemisphere and to the left in the southern hemisphere, and so to give us the north-east and south-east trade winds. Near the equator itself the hot, moist air rises as we should expect it to and is replaced by the relatively cool and heavy air of the trade winds. This is the belt of doldrums, in which calms and light winds prevail, with a slow general drift of air from east to west.

This completes the scheme of the general circulation of the atmosphere. Near the equator is the belt of doldrums, calms and light winds, in which the hot moist air is generally ascending and giving rise to heavy rain. The average position of the middle line of the doldrums is not exactly on the equator but a little north of it. In June and July, when the northern hemisphere is enjoying its summer, the hottest region, and therefore the centre of the doldrums, lie some distance north of the equator. In December and January, when it is summer in the southern hemisphere, the hottest region, and therefore the centre of the doldrums, lie a little south of the equator.

On either side of the doldrums are the trade winds, blowing from north-east in the northern hemisphere, from south-east in the southern hemisphere. These winds are steady in direction and maintain, day in, day out, the force of a moderate breeze, with only rare interruptions by calm or storm. The weather is generally fine, the sky about half covered with small fleecy clouds. The trade winds are properly developed only over the oceans, where they extend to about latitude 20 or 25 in each hemisphere.

Beyond the trade winds again, in about latitude 30 of each hemisphere, are other belts of calms and light airs. Unlike the doldrums they are regions of high pressure, intensely fine weather with very few clouds and practically no rainfall, where sailing ships used to lie becalmed—

"As idle as a painted ship
Upon a painted ocean."

These are the sub-tropical anticyclonic belts, sometimes called the "horse latitudes."

Poleward of the anticyclonic belts are the zones of westerly winds, the "temperate westerlies," because they include the greater part of the temperate regions. On the equatorial side where the pressure is high the weather is mainly fine and the winds light, but nearer the poles the winds become stronger and stormier and the rainfall heavier. Southern England occupies a position near the middle of the north temperate westerlies. Towards the poles, in about latitude 60 north and south, the zones of westerlies end in regions where the average barometric pressure at sea level is lower than anywhere else on the earth's surface. These sub-polar low pressure areas are limited to the oceans, and in the northern hemisphere are found only in the North Atlantic—the Icelandic Low—and in the North Pacific—the Aleutian Low, so called from the Aleutian Islands west of Alaska. The Icelandic Low especially is a region of great storminess. The Aleutian Low is found only in winter and disappears in summer; it is noteworthy for its fogs, rivalling the Great Bank of Newfoundland in this respect. In the southern hemisphere, where the great Southern Ocean completely encircles the globe, instead of isolated centres there is a trough of very low pressure girdling the Antarctic continent, with probably centres of storminess in the Ross Sea and Weddell Sea. The terrific winds, the great waves, and the floating ice number the poleward parts of the Southern Ocean among the most dangerous seas of the world.

Finally, on the poleward sides of the sub-polar low pressure areas the winds are again easterly, or rather north-easterly in the Arctic and south-easterly in the Antarctic. These winds, especially in the north, are much less regular than the trade winds, and can only be recognised to the north of the Icelandic and Aleutian low pressure areas. These polar areas—the "frigid zones" of the old school geography books—are very cold, with much floating ice on the seas, great cloudiness and frequent blizzards of snow. The junction between the polar east winds and the temperate west winds has attained great importance in modern meteorology, and under the name of the "polar front," has been recognised as the main birthplace of the storms of our latitudes, as described in Chapter IV.

The various zones which have been described above—doldrums, trade winds, sub-tropical calms, westerlies, polar fronts, and polar east winds—can only be seen clearly over the oceans and the western coasts of the continents. We may illustrate them by Fig. 1, which shows the average distribution of barometric pressure along the meridian of 20 west, which skirts the east coast of Greenland, crosses Iceland, and then extends entirely over the North and South Atlantic Oceans until it strikes the Antarctic continent. A section from north to south across the Pacific would be closely similar, but over the continents the sections would be different. A discussion of the pressure distribution over the continents, however, must be postponed to a later chapter.

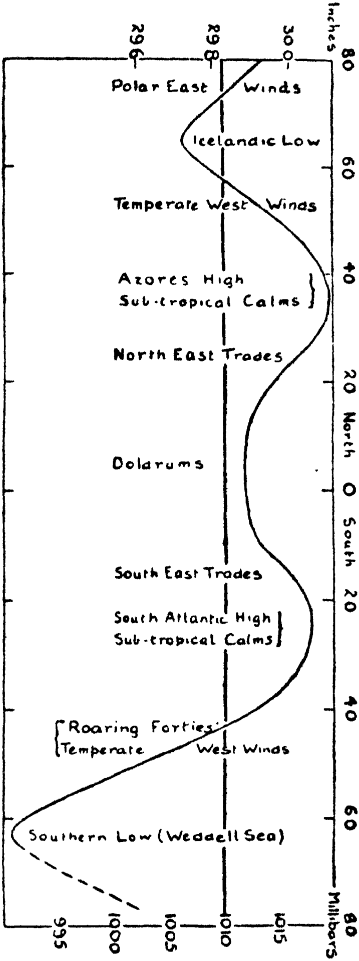

FIG. I.—DISTRIBUTION OF PRESSURE ALONG 20° WEST.

The pressures in Fig. 1 are shown in two units. On the left are the familiar inches and tenths, which until fourteen years ago were engraved on all British barometers. On the right the same lines are marked in millibars, the modern scientific unit for the measurement of the pressure of the air. A barometric pressure in inches means the length in inches of a column of mercury, under certain standard conditions of temperature, etc., which the pressure of the air is able to support. Expressing a pressure in this way in terms of a unit of length is like selling cheese in terms of a length of cloth which weighs as much as the amount of cheese required. No one would think of going into a shop and ordering a yard of cheese, but, apart from custom, it would be no more absurd than to talk of a pressure of thirty inches. The millibar is an actual unit of pressure, just as the pound is a unit of weight—but this is by the way. Here it is enough to remark that a pressure of thirty inches of mercury under certain standard conditions is equivalent to 1,012 millibars.

CHAPTER III

THE CONDITIONS IN THE UPPER AIR

If you take two thermos flasks of exactly the same size and weight, uncork them, put one (upside down) in a hot oven, the other (right way up) in an ice-chest, and after a time cork them up and then take them out and weigh them on a delicate balance, you will find that the flask from the ice-chest is a little heavier than the flask from the oven. Both contain the same volume of air, but the air in the flask from the ice-chest is heavier than the air in the flask from the oven, because cold air is heavier than hot air when both are subjected to the same pressure, and also if both are equally moist. It is the lightness of hot air which makes the smoke from fires go up chimneys; if hot air were heavier than cold air, we should have to build chimneys downwards and make sewers to carry away the smoke. The lightness of hot air was made use of in the first balloon, which was filled with air, but had an opening at the bottom, under which a fire was lit; when the air in the balloon was sufficiently warmed the balloon rose. The toy fire-balloons of the present day use the same principle. Remember, then, that hot air rises and cold air sinks—and now you see why the thermos flask had to be put in the oven upside down.

Instead of talking about the weight of air, it is customary to refer to its *density,* which means simply the weight of a sample of unit volume, such as a cubic foot or a cubic metre. The meaning of the word "density" can, perhaps, be better understood by reference to something solid, such as a glacier. We cannot pick up a glacier and weigh it on a pair of scales, but we can cut a sample of it, one-foot cube, and weigh that. Then, if we think that our sample is representative, we can say that the density of the glacier is so many pounds per cubic foot. Similarly, by taking proper precautions, we can weigh a sample cubic foot of air. If we find that it weighs an ounce, we say that the density is one ounce per cubic foot.

In comparing the density of hot air with that of cold air, we supposed that both were subjected to the same pressure. This proviso was necessary because the density of air depends on this pressure as well as on the temperature. Air is very "elastic"; if the pressure on a cubic foot of air is decreased, that mass of air expands and occupies more than a cubic foot, and its density—that is, its weight per cubic foot—decreases. Air at sea-level is subjected to the downward pressure of all the air above it; this pressure is equal to the downward pressure of a column of mercury about 30 inches high, or of a weight of about 14½ lbs. to the square inch. The summit of a mountain a mile high has about one-sixth of the atmosphere below it and only about five-sixths above it, and there the downward pressure of the air supports a column of mercury only 25 inches high instead of 30 inches. The barometric pressure becomes less and less the higher we go.

We see, then, that when air is raised from sea-level to the summit of a mountain, the pressure on it is relaxed, and it expands. This seems simple enough, but this simple fact is at the root of one of the most important ideas in the whole science of meteorology—that is, the cause of rain. Mixed with air there is always some water vapour, but the quantity is strictly limited. A cubic foot of air at a given temperature can hold so much water vapour and no more, and when it has reached the limit of its capacity it is said to be *saturated*. The colder the air the less the amount of water vapour which it can hold, and if air which is saturated with water vapour is cooled, some of the vapour is condensed into water droplets, and a cloud is formed. If the air is cooled still further, these droplets become so numerous that some of them collide and join together into larger drops which fall as rain. If the air is very cold, the droplets as they form crystallise into snowflakes. The only way in which rain can be produced is by cooling air which is already saturated with water vapour so that part of this vapour is condensed.

The obvious way to cool air is to take heat away from it, either by bringing it against a cold surface or by allowing it to radiate its heat away. Nature seldom does things in the obvious way, and in producing rain Nature achieves the seemingly impossible feat of making air cold without taking any heat away from it. This is done by allowing the air to expand, for whenever air expands, unless heat is given to it, it grows colder, and whenever air is compressed, unless heat is taken away from it, it grows warmer. We have seen that when air is raised to a higher level it expands, and this is Nature's way of cooling the air and causing rain. When air descends it is compressed and grows warmer. In the atmosphere the air is continually moving up and down, with the obvious result that the temperature decreases with increasing height. The rate can be calculated, and it is found that the temperature of dry air should decrease by a little more than five degrees for each thousand feet of height.

As one goes up in a balloon or climbs a mountain the air generally becomes colder. However hot it is at sea-level, if one goes high enough the temperature falls below freezing-point, and even on the equator the highest mountains are snow-capped throughout the year. The average decrease is found to be between three and four degrees for each thousand feet of height. The most important reason why the rate of decrease actually found is not as great as the theoretical rate of just over five degrees per thousand feet due to the expansion of rising dry air is that in the atmosphere the air is never quite dry; it always contains some water vapour. When the rising air becomes so cold that it cannot hold all the water vapour which it has carried up, the surplus is condensed into water droplets or ice crystals. The heat which was used up in evaporating the water is set free again when it is condensed, and this supply of heat at the level of the clouds lessens the rate at which the temperature decreases upwards.

The elevation of moist air, and its consequent cooling by expansion, is practically the only way in which rain is formed, but the air may be raised in several different ways. When the wind blows towards a long range of mountains the air has to rise in order to cross the crest; the rain which is caused by the resulting cooling is called *orographic* rain, because it depends on the relief or orography of the country. When a moist wind blows steadily against a high range of mountains, as the south-west monsoon of India blows against the Khasi Hills of Assam, the orographic rainfall is exceedingly heavy. The shape of the Khasi Hills is such that the wind in some places is turned almost vertically upwards, and these places are among the rainiest in the world. The average rainfall of Cherrapunji, in Assam, is 424 inches a year, compared with 25 inches in London. The wettest places in the British Isles are found where the moist south-west winds rise over the mountains of Snowdon, Cumberland, and western Scotland, giving an average rainfall of nearly 200 inches a year.

Another way in which air is forced to rise is by convergence or the coming together of winds from different directions. If to the northward of any place a north wind is blowing, to the westward a west wind, to the southward a south wind, and to the eastward an east wind, the air from all sides is coming together at that place, and it can only get away by rising. The air from different directions need not rise equally; if the south wind is warm and the north wind cold, the warm air from the south will rise over the cold wind from the north. But, obviously, with winds converging from all directions like this, some air must be forced upwards. This example is extreme; it very rarely happens that the wind is blowing directly towards any place from all sides, but the same result would be obtained if the winds blew obliquely inwards. If the wind to the northward were north-east, to the westward north-west, to the southward south-west, and to the eastward south-east, the winds would still converge, though obliquely or spirally instead of directly. This oblique convergence of air occurs in cyclones, as described in the next chapter, and the rain which it causes is called *cyclonic* rain.

The third way in which air is forced to rise is by local heating. On a hot summer afternoon, looking along a level, tarred road or a stretch of sand, distant objects appear to shimmer. This shimmering is due to thin threads of hot air which are rising from the heated surface. When the threads get thicker and rise far enough, small woolly cumulus clouds are formed; these mark the level at which the rising air has cooled by expansion so much that its water vapour has condensed as cloud. Sometimes the ascent becomes still more vigorous, and under favourable conditions even violent, and the air ascends in thick columns instead of in thin threads; these conditions produce summer thunder-showers. This type of rain can only occur when the lower layers of air become so hot, compared with the upper layers, that the air becomes top-heavy or unstable, and quite a small disturbance causes the upper and lower air to change places, hence these showers are called *instability* showers. It must be carefully remembered, however, that when the air is unstable the higher layers of air are not actually heavier than the lower layers. Such a state of affairs rarely, if ever, occurs; what happens is that the surface air is *potentially* lighter than the upper air. This means that the surface air, although at the moment heavier than the upper air because of the greater pressure to which it is subjected, yet if it were raised to the same level as the upper air it would be lighter than that air. A sufficiently rapid upward decrease of temperature to make the air unstable can also be caused by bringing in very cold air at a high level over warm surface air. Generally speaking, in this country the isolated, thundery showers of summer afternoons are caused by the heating of the surface air without any change in the upper layers, while widespread, severe thunderstorms require in addition to warm air at the surface the presence of an unusually cold layer in the upper air.

We have seen that the temperature decreases upwards at the rate of three or four degrees per thousand feet. There seems to be no obvious reason why this decrease should not continue indefinitely upwards to the top of the atmosphere or until the temperature falls to somewhere near the absolute zero. Until nearly the end of the nineteenth century, it was tacitly assumed that such must be the case, but several meteorologists were actively engaged in "sounding the ocean of air," and their persistence met with astonishing results.

Owing to the decrease of the density of the air as one goes upwards, above a height of about five and a half miles or 30,000 feet, there is not enough air for human beings to live. In 1862 James Glaisher, the pioneer of meteorological ballooning, reached a height of nearly six miles, when he became unconscious. In 1901 Berson, a German balloonist, reached a height of six and a half miles; he took an artificial atmosphere with him in the form of a supply of oxygen, but even with this aid he lost consciousness. Since man cannot safely go above six miles, the only thing to do is to send the balloon without the man. A small spherical balloon is filled with hydrogen, the lightest of all gases, and attached to a light, self-recording instrument. The instrument in use in England, which was designed by Mr. W. H. Dines, weighs only two and a half ounces, and consists of an aneroid barometer and a metallic thermometer in an aluminium case. The barometer and thermometer carry levers with sharp points, and scratch their records on a metal plate, which is afterwards read with the aid of a microscope. These sounding balloons, as they are called, have reached a height of twenty miles, or nearly three times the height of Mount Everest. Finally, the balloon bursts or develops a leak and falls back to the ground; being all metal, the instrument is not hurt by its thrilling experience, and an attached card directs the finder to return it to the Meteorological Office, where he may claim a small reward. Most of the instruments do, in fact, find their way back home.

Ascents with these instruments soon revealed the surprising fact that at a height of about seven miles over Europe the temperature ceases to fall, and above this height it remains constant or even increases a little. This upper layer, in which the temperature changes very little with increasing height, is termed the *stratosphere,* while the lower layer, in which temperature decreases upwards, is termed the *troposphere.* The junction between the troposphere and the stratosphere is called the *tropopause.* When similar ascents were made in other parts of the world, the tropopause was met with at a height of only about three miles near the poles, while close to the equator it was not found until the balloons had reached a height of more than ten miles. This difference in the height of the tropopause leads to a result which is even more startling than the existence of the stratosphere — namely, that at a height of about ten miles the air is warmest over the poles and coldest over the equator. A little arithmetic will easily show how this comes about. In the troposphere the temperature decreases upwards at an average rate of about 20° in each mile. Near the equator the average temperature of the earth's surface is about 80°, but the top of the troposphere, being ten miles higher, is 200 degrees colder— that is, its temperature is about minus 120°. Near the north pole the average temperature a little above the earth's surface is only about 20°, and this falls to about minus 40° at a height of three miles. This is the top of the troposphere, and the temperature does not fall any lower, but is still minus 40° at a height of ten miles, or 80 degrees warmer than at the same height over the equator. This reversal of the distribution of temperature at high levels was quite unsuspected until it was revealed by the sounding balloons.

The latitude is not the only factor on which the height of the tropopause depends. It is a little higher in summer than in winter, because in summer we are, for meteorological purposes, nearer the equator than in winter. But there is a much greater difference, in temperate regions, between the level of the tropopause in bad weather, that is, during cyclonic conditions and low barometric pressure at the surface, and fine weather, or anticyclonic conditions and high barometric pressure at the surface. In England the average height of the tropopause above cyclones is only five and a quarter miles, above anticyclones seven and a half miles. This means that the temperature goes on falling to a much greater height above anticyclones than above cyclones, and the stratosphere above anticyclones is colder than that above cyclones.

So far these facts about the stratosphere, though not without interest for their own sake, seem to have no bearing on the happenings on the earth's surface. The higher levels of the atmosphere would seem to be of no more direct interest to humanity than the bottoms of the deepest oceans. But it is not really so; everything that happens in the air above us affects us, because all things have weight and press downwards. The pressure of the air in the stratosphere is transmitted downwards through the troposphere, and contributes its quota to the total pressure of the air as recorded by a barometer at sea-level, just as the pressure, or weight, of the topmost of a pile of pennies on a balance is transmitted downwards through the other pennies of the pile, and contributes its quota to the weight of the whole pile.

Now imagine two mountains, each six miles high, one near the north pole and the other near the equator. The air above these mountains is coldest, and therefore heaviest near the equator, warmest and lightest near the pole, and the pressure which would be shown by a barometer on the summit of the equatorial mountain is higher than that on the summit of the polar mountain. The density of the air between a height of six miles and sea-level is greater near the pole than at the equator, because in the lowest six miles of the atmosphere the polar air is so much the colder, and if all the air above six miles were suddenly swept away the pressure at sea-level, though everywhere less than now, would be greatest near the poles. The actual pressure at sea-level is that of the whole atmosphere, that above six miles being added to that below six miles, and since what the polar air lacks in density at high levels it makes up for near the ground, the actual barometric pressure at sea-level does not differ much at the pole and the equator. We may illustrate this crudely by supposing that we have twelve halfpennies and twelve sovereigns (a sovereign weighs more than a halfpenny), which we arrange in two piles, one to represent the polar atmosphere, having six sovereigns below and six halfpennies above, and the other to represent the equatorial atmosphere, having six halfpennies below and six sovereigns above. Both piles weigh the same, but if we weigh only the top six coins in each pile the equatorial pile weighs the more.

But suppose we exchange a halfpenny from the polar pile for a sovereign from the equatorial pile. Now the polar pile weighs more and the equatorial pile less. The fact that the stratosphere in temperate regions is higher and colder than usual over anticyclones means that part of the tropical stratosphere has been transplanted to temperate latitudes—we have, so to speak, put a sovereign in place of a halfpenny. The total pressure at sea-level is increased. In the same way, when a part of the warm polar stratosphere is transplanted to temperate latitudes the effect is to put a halfpenny in place of a sovereign. The total pressure at sea-level is decreased, and we have an area of low pressure, a cyclone, or "barometric depression." But that is another chapter.

CHAPTER IV

CYCLONES AND ANTICYCLONES

In the early days of meteorology no difficulty was found in explaining the origin of cyclones and anticyclones. In cyclones the surface air is moist, and in winter, at any rate, generally warm. In anticyclones the surface air is dry, and in winter in this country generally cold. Warm air is lighter than cold air, and moist air is lighter than dry air. A patch of warm moist air, therefore, makes a region of low pressure, or a cyclone, while a patch of dry cold air makes a region of high pressure, or anticyclone. In a cyclone the warm moist air tends to rise, and an ascending current is formed. The ascending air immediately begins to expand and to cool, but it is so moist that this cooling quickly brings about condensation of the water vapour into clouds and rain. The heat set free by condensation ensures that the rising column of air shall remain warmer than the surrounding air up to very great heights. To quote from an old textbook, " this column of heated air may be compared to that in chimneys and stove pipes." The air rises up this invisible chimney, just as the relatively warm air rose out of the thermos flask in the ice-chest of Chapter III., and flows away out of the top of the cyclone. This still further diminishes the pressure in the interior of the cyclone, and air tends to rush in on all sides towards this central low pressure.

But here the rotation of the earth comes in, as in the general circulation described in Chapter II., and deflects the winds to the right (in the northern hemisphere) until they flow along the isobars. Hence the winds go round and round the cyclone in the opposite direction of the hands of a clock laid on the table face upwards. Near the earth's surface friction with the ground checks the wind in its free movement along the isobars and allows it to blow slightly inwards towards the centre of the cyclone, but only a little air can get into the centre in this way, and in its effort to fill up the gap left by the rising air the wind goes round the centre faster and faster, and that is why the winds in a cyclone are often so strong.

An anticyclone was supposed to be just the opposite of a cyclone. The air, being cold and dry and therefore heavy, sinks towards the surface of the earth, where it flows obliquely outwards from the centre. Since the air is descending, there is no condensation, and the weather is fine and free from cloud.

This theory of the nature of cyclones and anticyclones held the ground for a long time, but meteorologists were not entirely satisfied with it, and finally the investigation of the upper air by sounding balloons showed that in this country at least it was incorrect. It was found that the air in a cyclone is not warmer than the surrounding air, and the air in an anticyclone *is not colder than the surrounding air. In most* cyclones and anticyclones the reverse is the case; except just at the surface, the air in a cyclone is generally colder than the air in an anticyclone. Taking the averages of a large number of balloon ascents in this country, Mr. W. H. Dines found that half a mile above the ground the cyclonic air is the colder by six degrees, and with increasing height the difference goes on increasing until, at a height of four miles, the cyclonic air is 21° colder than the anticyclonic air. Evidently, then, the cyclone does not owe its low pressure to a column of warm air in the lower atmosphere.

The cyclone does, in fact, owe its low pressure to a column of warm air, but the base of the column is not the earth's surface, but the base of the stratosphere, at a height of five and a quarter miles. The reason for the low pressure in a cyclone is that the stratosphere, above it, being low, is relatively warm (about 53 degrees below zero), while above an anticyclone the stratosphere, being high, is cold (about 70 degrees below zero). Another difficulty of the old theory was that when attempts were made to follow the course of the winds from one hour or day to another, it was found that the air does not go round and round the centre of a cyclone. Some of it goes round once, but a large part of the air only completes a half or a third of a circuit before it is lost to view, so that the idea of a cyclone as a circular whirl is some way from the truth.

The methods of daily weather forecasting in use in Europe and North America depend mainly on the study of cyclones and anticyclones. Meteorological observations are taken at the same hour at a number of "stations" in each country and are sent by telegraph to the central weather offices. The various weather services exchange the observations in their own countries by telegraph or nowadays by wireless; observations from ships are also received by wireless. These observations are plotted on maps, on which are drawn isobars, or lines along which the barometric pressure is the same. Until about fifteen years ago it was supposed that isobars should follow smooth flowing curves, without kinks, and, in fact, that in a perfect cyclone the isobars should be beautifully circular and concentric. A barometer reading which did not fit into one of these systems of smooth curves was supposed to be wrong, but there were not many such misfits, because telegraphy is expensive, and telegraphic reporting stations were not so numerous as meteorologists could wish. It is much easier to draw smooth isobars when there are only a few stations than when there are a large number. Even so, however, the idea was growing up that some of these difficult readings were not misfits after all, but really did mean kinks in the isobars. These kinks were found to be associated with squalls which extended in a long line across the country, and so were called "line-squalls."

Then came the Great War. Meteorological information suddenly became of enormous value, jealously guarded and not imparted to neutrals, who had to do the best they could without it. The Norwegian meteorologists tried to make up for the absence of information from belligerent countries by establishing a large number of stations in their own country. The detail so obtained showed that the kinks were not only real, but as significant as the rest of the isobars, and this resulted in a new idea of the structure of cyclones. The new idea is termed the " polar front theory," and is associated with the names of V. and J. Bjerknes, father and son.

The polar front has already been referred to in Chapter II. as the dividing line between the cold polar east winds and the temperate west winds. On either side of the polar front there are two streams of air moving in opposite directions, one cold, dry, and relatively heavy, the other warm, moist, and relatively light. It is one of the laws of Nature that two different streams cannot flow side by side or one over the other in different directions or at different speeds and maintain a straight boundary between them; they develop " waves." The best-known examples are the waves of the sea—not the breaking waves of the shore, but the long swells of the open sea—which are caused by a current of air, the wind, flowing over the sea. There can be waves between different streams of air; the crests of such waves are sometimes marked by long, parallel bands of cloud. Similarly, waves form in the polar front between the easterly and westerly winds, and move eastwards. For convenience we will limit the description of subsequent happenings to a cyclone in the temperate zone of the northern hemisphere.

The fore part of the wave consists of warm air (technically called " equatorial " air in contrast to the cold or " polar " air), which is moving from west-south-west to east-north-east. The polar front is not a vertical wall, but slopes gently upwards towards the pole, and the equatorial air of the fore part of the wave runs up this slope of polar air as a sea wave runs up a shelving beach. This eastern boundary between the advancing warm air and the polar front is called the "warm front" (see Fig. 2).

Meanwhile the rear of the wave in the polar front, consisting of cold polar air moving from the north-east, is also advancing, but, being heavy, this air thrusts under the equatorial air and raises it bodily. At this stage the lowest pressure is found at the northern end of the warm front, and the advancing wedge of polar air curves round this centre until it is advancing from north and finally from north-west, west, or even south-west, and the wave begins to "break." This advancing wedge of cold air is called the "cold front." At this stage the cyclone is fully formed, but is still growing in intensity, and is said to be young. Next the cold front overtakes the warm front, and the cold air encloses a mass of warm air and lifts it entirely off the ground. At this stage there is no warm air on the surface, but the centre of the cyclone is still occupied by a mass of warm air aloft. The cyclone is now in middle age. Finally the warm air disappears, and the only sign of its former presence is a swirl in the upper air and some irregularities in the temperature distribution at the surface. The core of the cyclone is now occupied by cold polar air, and the cyclone is "dying."

At first sight these pictures of a cyclone seem to be

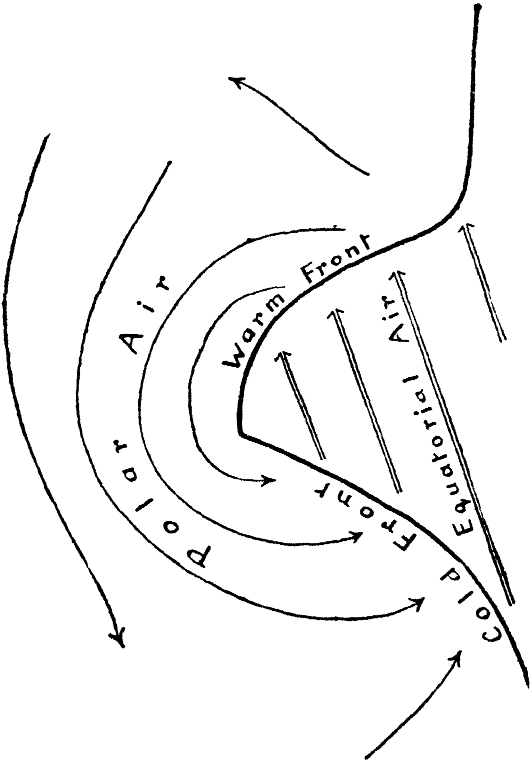

FIG. 2.—STRUCTURE OF A CYCLONE.

inconsistent with the statement that the centre of a cyclone in the troposphere is cold. Our knowledge of the structure of cyclones, especially at high levels, has not yet reached the stage at which one can be dogmatic, but the explanation appears to be that the great majority of the cyclones which reach the British Isles are dying, having passed through their birth, youth, and middle age far out in the Atlantic. In North America, where young cyclones are fairly frequent, ascents with sounding balloons do sometimes reveal the presence of warm centres.

It will easily be seen that the advance of the cold front in the rear of a cyclone leaves the polar front farther south than it was before the cyclone developed. This means that the next cyclone will form farther south than the first. This, in turn, pushes the polar front still farther southwards, and the third cyclone forms south of the first two. Such a series of cyclones is called a " cyclone family "; if we regard the first cyclone as the parent, it may have two, three, or even four descendants—a son, a grandson, and so on. The descendants are often smaller than the parent, and they are born, not only farther south, but farther east as well, so that they often reach the coast of Europe in a more vigorous condition than their ancestors. The line of descendants cannot go on indefinitely, because the cold fronts have to be supplied from the reservoir of cold air in the Arctic, and when this is exhausted the formation of cyclones ceases temporarily until the reservoir is filled again. Sometimes, however, the process goes on long enough for a cold front to reach the north-east trade wind, and then the cold polar air passes straight down the Atlantic corridor to the doldrums.

The cause of rain in cyclones is the elevation of the warm moist equatorial air above the cold polar air. On the warm front the equatorial air rises gradually up a long slope, and the rain which forms in the fore part of a cyclone is steady but not violent. On the cold front the equatorial air is lifted with a jerk by the wedge of polar air, and there is a short but heavy shower of rain, sometimes with hail and thunder. Even when the cyclone is dying, discontinuities or rapid changes of temperature in a short distance still remain and produce similar effects, for all polar air has not the same degree of cold, and often a dying cyclone is more complicated than a young one.

The transfer of equatorial air polewards along the warm front, and the advance of polar air towards the equator in the cold front, result in a great interchange of air between low and high latitudes. This is the purpose for which the winds were made; we saw in Chapter II. that they were unable to carry it out in a simple and direct fashion because they were prevented by the earth's rotation. So we see that cyclones are not the casual phenomena which they were once supposed to be—mere ripples on the orderly procession of the great wind systems of the globe—but are an essential part of the world circulation.

Between two cyclones is an area of high pressure, which gives us a day or two of light winds and fine weather between storms. This is an anticyclone in the sense that the pressure is high by contrast with the low pressures which precede and follow it. But such anticyclones consist of cold polar air, and are really members of the cyclone family, moving eastward with the cyclones which precede and follow them; they are birds of passage, here to-day and gone to-morrow. The long spells of fine weather which we do sometimes enjoy are due to anticyclones of a different sort, described on p. 34. Here the high pressure is due to a piece which has become detached from the great sub-tropical anticyclone of the Azores and has wandered slowly north-eastward. Such anticyclones consist of warm equatorial air and owe their high pressure to the high, cold stratosphere which they have brought with them from lower latitudes. They are of large area and move very slowly, and so they give us long spells, often three weeks or a month, of fine, dry weather.

It is fashionable to grumble at the British climate, especially during spells of cyclonic activity, but really we should be grateful for the infinite variety with which the constant succession of cyclones and anticyclones provides us. The continuous fine weather of the lands of sunshine is monotonous and enervating; the changeability of our climate is refreshing and invigorating. It is quite possible that Ellsworth Huntington is right when he attributes the dominating position which the inhabitants of the stormy temperate regions hold in the world's affairs to their climate, and that the superman is not Nordic or Aryan, but Cyclonic.

CHAPTER V

CLIMATIC ZONES

THE succession of cyclones and anticyclones crossing the British Isles brings constantly varying weather. One day may be hot and brilliantly sunny, the next warm and rainy, the third cold and showery. The terms hot and cold are comparative; they mean hot or cold compared with the average temperature of the season. The average temperature, the average rainfall, and so on, together make up the average weather, or the *climate*. We may talk of the wet weather of Derby Day, or even of the wet weather of 1927, but the lady who, reproached with not having visited a friend for twenty years, excused herself by saying, "Look what weather we've been having!" should really have said (supposing she was not exaggerating), "Look what a climate we live in."

As we generally speak of weather in terms of temperature and rainfall, a day being fine and hot, or cold and wet, so we describe climate chiefly in the same terms. A rainy climate is generally (though not always) a moist, cloudy climate with little sunshine, so that this description covers most of the features of weather which are of general interest. The humidity of the air is, however, an important element of climate quite apart from rainfall, and some rather startling effects have been attributed to it. For example, a dry climate tends to restlessness, and this in turn to thinness, and in the course of many generations the inhabitants of a dry, cold climate tend to develop prominent noses, with long nasal passages, in which the air is warmed and moistened, while the inhabitants of warm, moist climates tend to develop small noses.

For the reasons given in the first chapter, temperature is highest near the equator and decreases towards the poles, and if in the first place we classify climates as hot, temperate, and cold, these climates will form belts or zones which encircle the earth roughly parallel with the lines of latitude. The average temperature and rainfall of the different latitudes are shown in Fig. 3. Rainfall depends mainly on the amount of rising air, which in turn depends to a large extent on the general circulation of the atmosphere. Thus we can speak also of zones of rainfall, though these are not nearly so definite as the zones of temperature. Near the equator we have a belt of heavy rainfall, the doldrums over the Atlantic and Pacific Oceans, the equatorial rainfall belt over the continents. This belt includes the great rainy basins of the Amazon and Congo Rivers, and as it gives a climate especially favourable for the growth of dense tropical forests, it is often termed the equatorial rainforest belt. In about latitude 30 of each hemisphere there is a belt of high pressure which is best seen over the oceans, but which can also be distinguished over most of the continents. These belts have a small and uncertain rainfall, and are the sites of most of

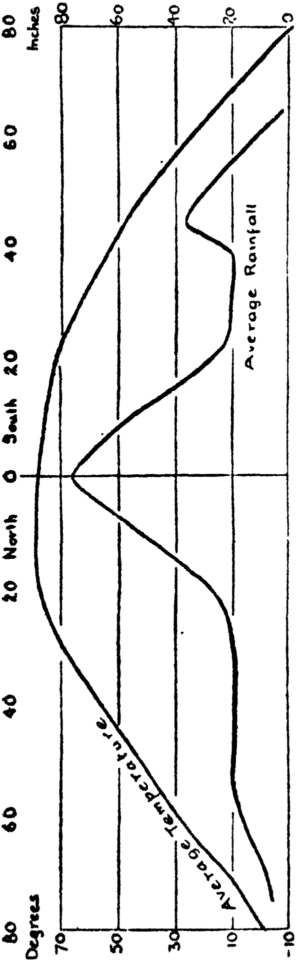

FIG. 3.—AVERAGE TEMPERATURE AND RAINFALL.

the great deserts of the world—the Sahara, Arabia, the Kalahari, and the deserts of Arizona and Australia.

On the poleward sides of the desert belts lie the storm-belts of the temperate regions. These again are naturally regions of heavy rainfall, and the temperate rain belt of the southern hemisphere is clearly shown in Fig. 3 as a crest of the rainfall curve in latitude 40 to 50 south. In the northern hemisphere the place which this belt would occupy happens to coincide with the greatest extent of the continents in Europe, Asia, and America, and as the interiors of great land masses tend to be dry because of their distance from the main source of water vapour in the oceans, the temperate rain belt of the northern hemisphere is not shown as a separate crest in the rainfall belt of Fig. 3, but only as a slackening of the fall from the equator to the north pole. Both polar regions are dry, because the air is so cold that it can hold but little moisture, and the ascent of a large amount of air yields only a small amount of precipitation. Thus the principal climatic zones are the equatorial hot, rainy belt, two sub-tropical hot, dry belts, two temperate rain belts, and two polar caps of dry, cold climate.

The equatorial rainfall belt is marked not only by cloudy skies and heavy rain, but also by a *uniformly* high temperature. The average temperature of a place near the sea-level is never far from 80° in any month; the midday temperature is never far from 85°, and the temperature between midnight and 6 a.m. is never far from 75°. There are very large areas near